

# Fluctuations in Hot and Dense Matter

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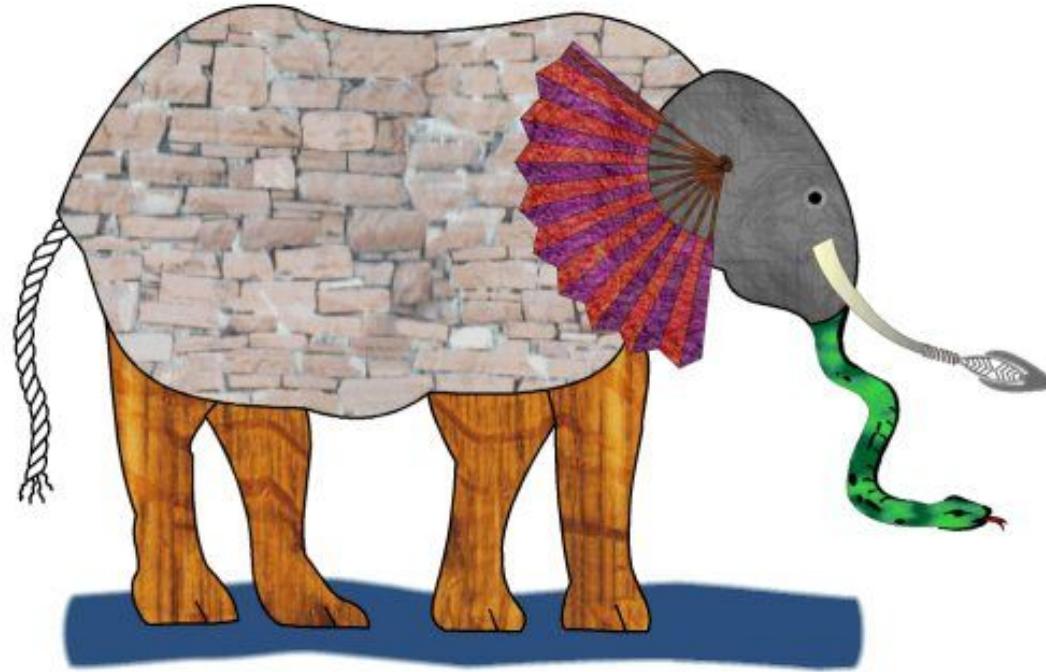
with Volker Koch, Lijun Shi & Marcus Bleicher

# Perspective

We've found QGP.

# Perspective

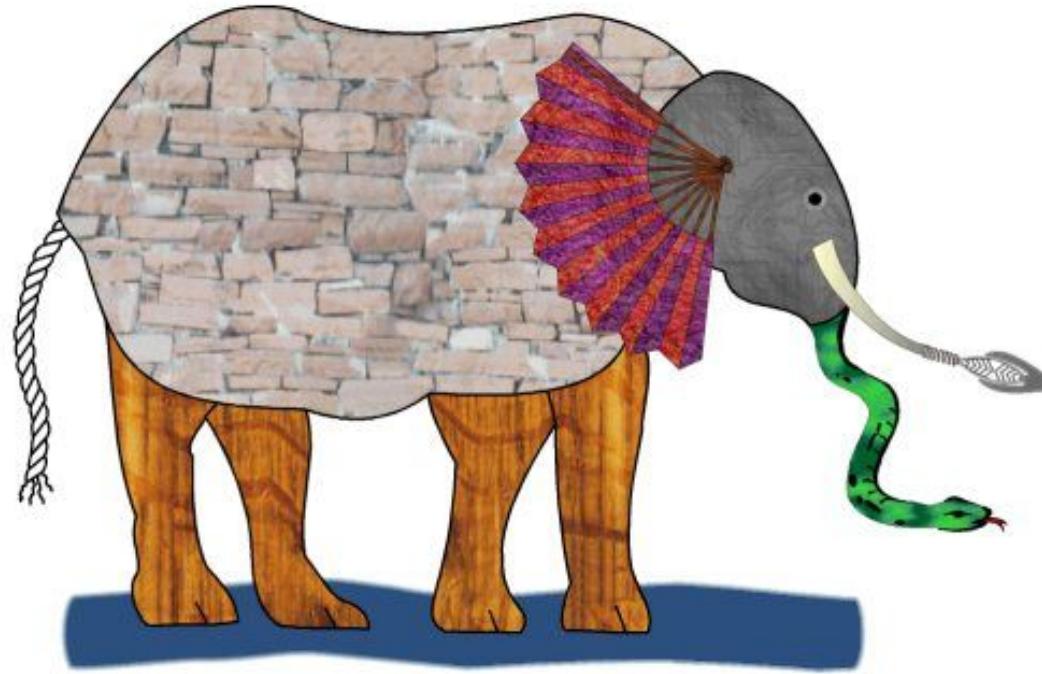
We've found QGP.



But is it a Wall, Spear, Snake, Tree, Fan or Rope?

# Perspective

We've found QGP.

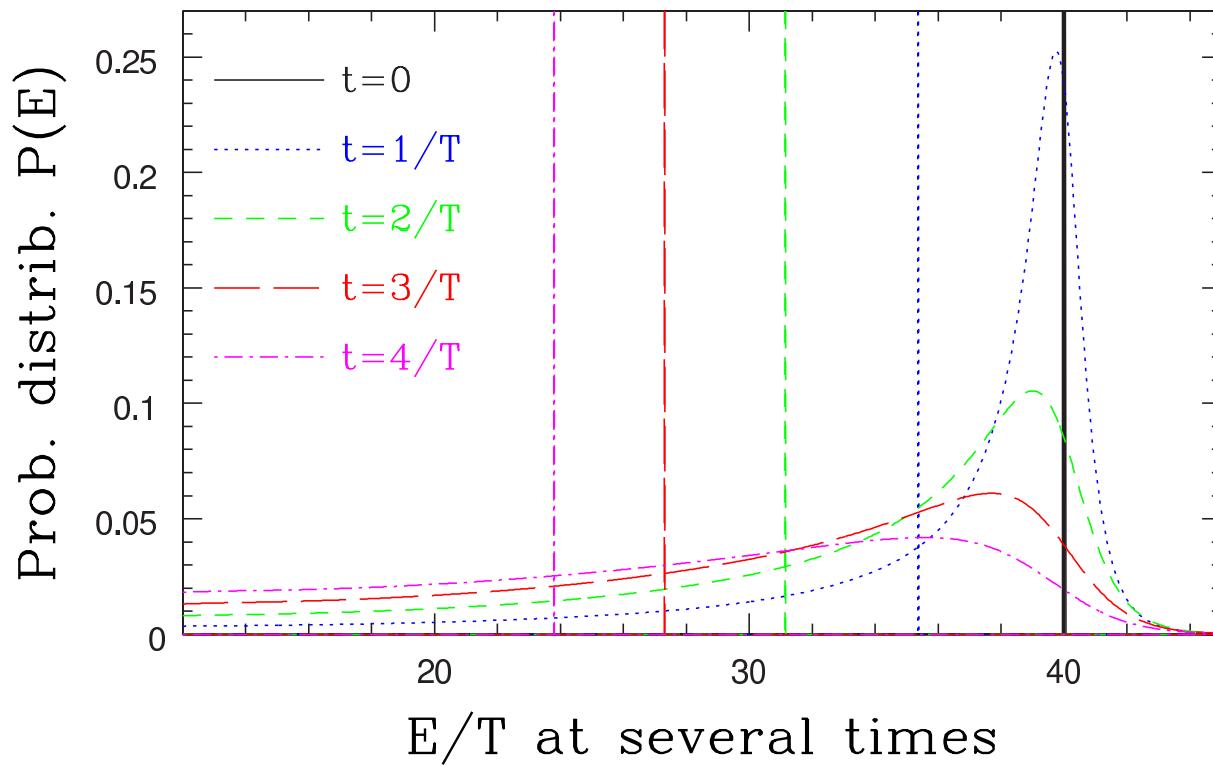


But is it a Wall, Spear, Snake, Tree, Fan or Rope?

We need to correlate information to get the full picture!

# Why fluctuations?

- Average can be (quite) misleading – I



Evolution of  
jet  $P(E)$ .  
(Jeon and  
Moore,  
PRC71:034901,  
2005)

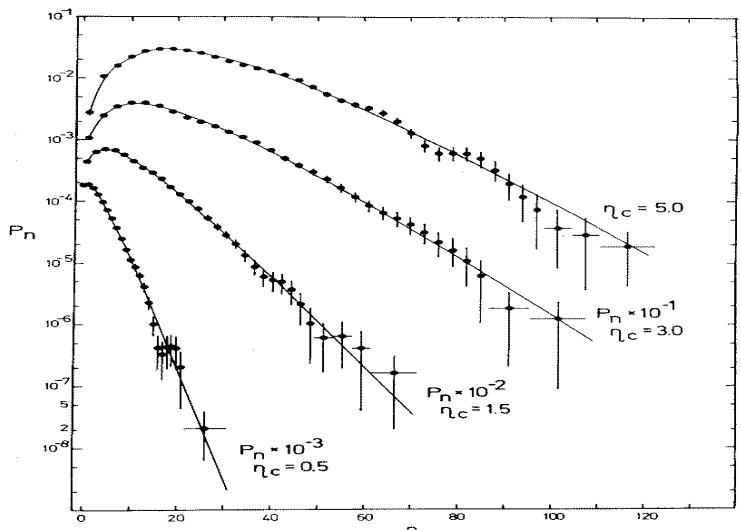
- Average can be (quite) misleading – II

- $p_T$  spectrum in  $P\bar{P}$  collisions (UA1 & UA5):

$$E \frac{d\sigma}{d^3 p} = \begin{cases} A \exp(-bm_T) & \text{Low } p_T. \text{ Bulk. Looks thermal.} \\ B(1 + p_0/p_T)^{-n} & \text{High } p_T \end{cases}$$

But

$$\langle \Delta N^2 \rangle = \langle N \rangle (1 + \langle N \rangle / k) \sim \langle N \rangle^2$$

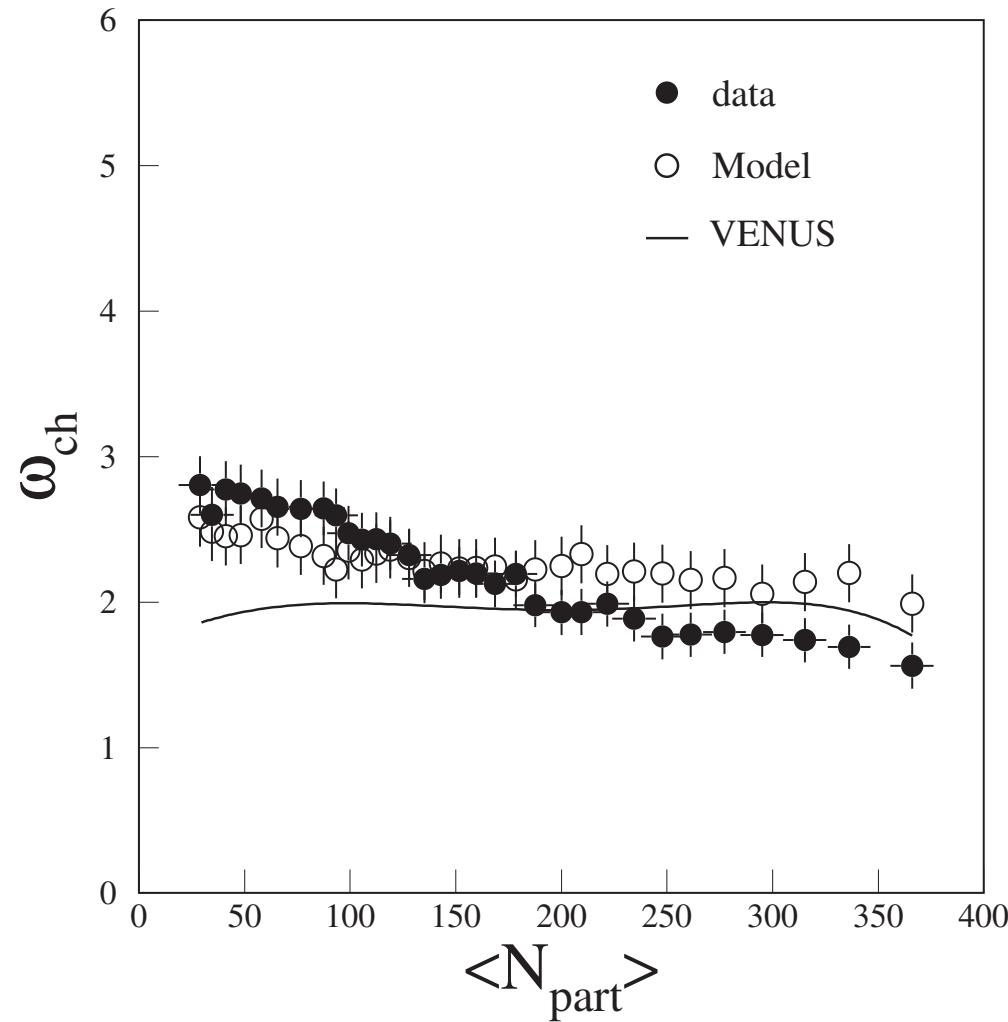


UA5 data

For  $|\eta| < 0.5$ ,  $\langle N \rangle = 3.01 \pm 0.03$ ,  
 $\langle N^2 \rangle - \langle N \rangle^2 = 8.41 \pm 0.23 \approx \langle N \rangle^2$

This is **not** a thermal spectrum!

# Cont.



A Curious data:  
WA98, PRC 65,  
054912, (2002)

# QGP $\approx$ Thermalized

## Consequences

- $P(E) \propto n_{\text{BE}}(E), n_{\text{FD}}(E)$
- $\langle (N - \langle N \rangle)^2 \rangle \approx \langle N \rangle \propto S$
- $\langle (Q - \langle Q \rangle)^2 \rangle \approx q^2 \langle N \rangle = \frac{1}{9} \langle N_d \rangle + \frac{4}{9} \langle N_u \rangle$
- ...

# Net Charge Fluctuations

- Motivations [Jeon & Koch + Asakawa, Heinz & Muller, PRL 85, 2000 ]
  - \* Quarks carry fractional charges
  - \* Gluons are abundant
  - \* In QGP (with appropriate degeneracy factors (12+12+16))

$$\langle \Delta Q^2 \rangle = (9/4) \langle \Delta N_u^2 \rangle + (9/1) \langle \Delta N_d^2 \rangle$$

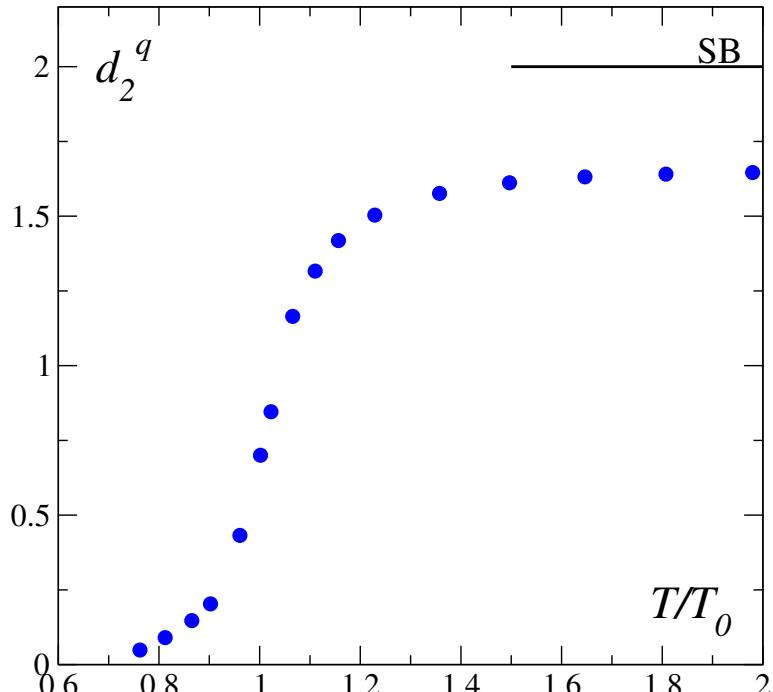
and invoking ‘parton-hadron duality’

$$\langle N_{\text{ch}} \rangle \approx (2/3)(\langle N_u \rangle + \langle N_d \rangle + \langle N_g \rangle)$$

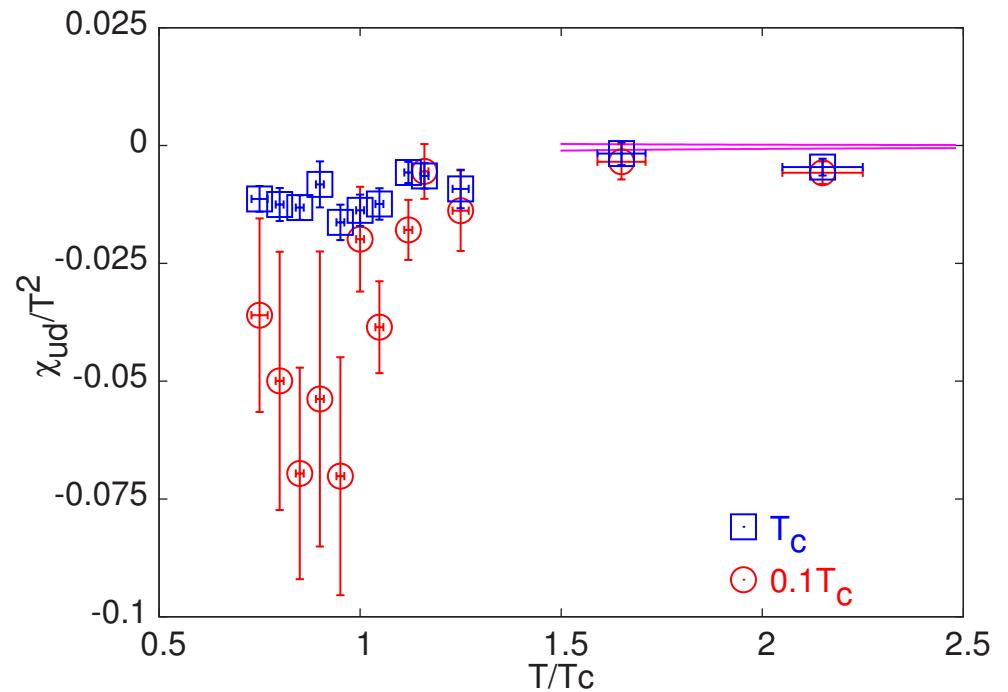
we get (and Lattice confirms it)

$$\frac{\langle \Delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle} \approx 1/4 - 1/3$$

# Data from Lattice

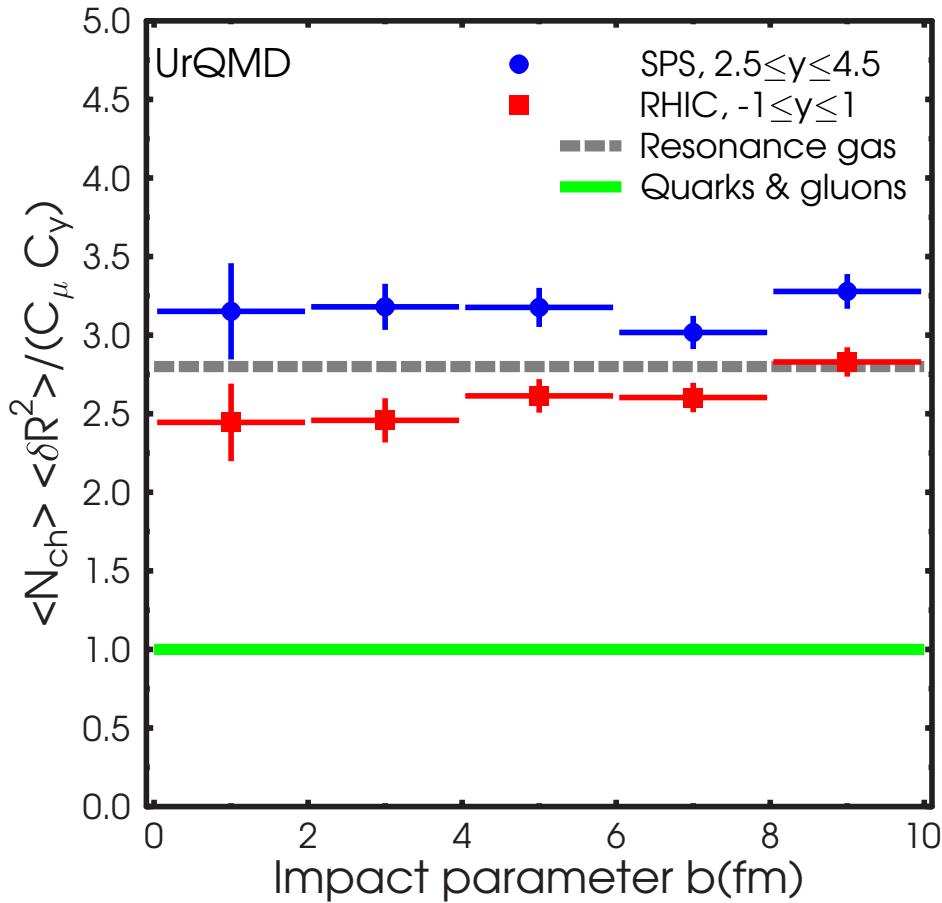


Quark number susceptibility  
S.Ejiri, F.Karsch and  
K.Redlich, PLB 633:275-  
282, 2006



u-d susceptibility,  
R.V.Gavai and S.Gupta,  
PRD73:014004, 2006

# UrQMD Study



Lesson 1: Rough estimate of thermal resonance agrees with UrQMD.

Lesson 2: The observed value will crucially depend on the length of the hadronic phase.

# STAR Data

- Usually given in terms of the ' $\nu$ -Dynamic'

Define

$$\nu_{+-} = \left\langle \left( \frac{N_+}{\langle N_+ \rangle} - \frac{N_-}{\langle N_- \rangle} \right)^2 \right\rangle = \left\langle \left( \frac{\Delta N_+}{\langle N_+ \rangle} - \frac{\Delta N_-}{\langle N_- \rangle} \right)^2 \right\rangle$$

and

$$\nu_{+-,\text{dyn}} = \nu_{+-} - \frac{1}{\langle N_+ \rangle} - \frac{1}{\langle N_- \rangle} = \frac{4}{\langle N_{\text{ch}} \rangle} \left( \frac{\langle \Delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle} - 1 \right)$$

- Data

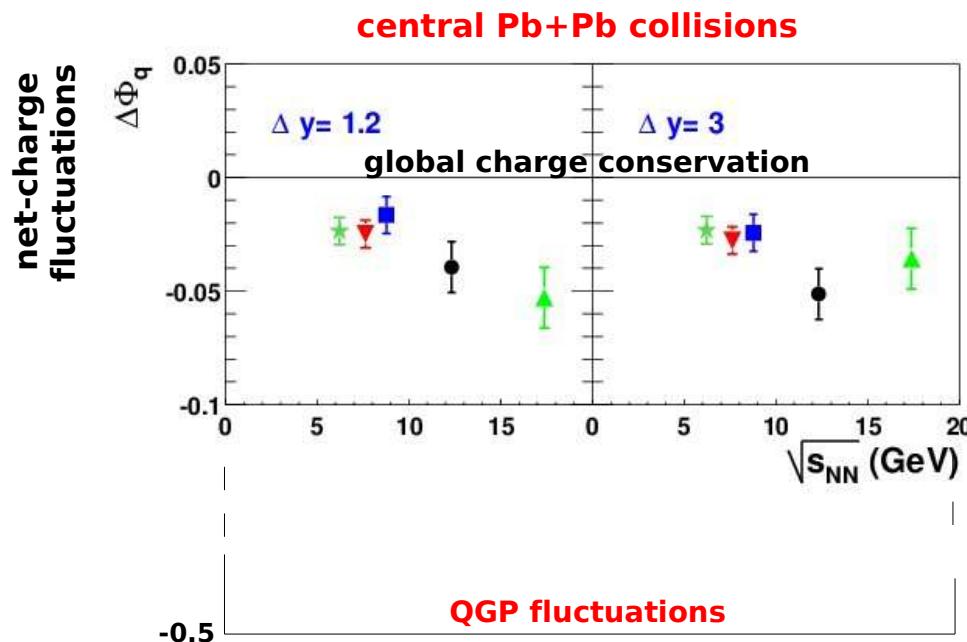
$$* \quad \langle N_{\text{ch}} \rangle \nu_{+-,\text{dyn}} \approx -1 -- 1.4$$

$$\text{or } \frac{\langle \Delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle} \approx 0.75 - 0.65 \implies \text{Consistent with hadronic gas}$$

# DATA from NA49

Marek Gazdzicki [Correlations and Fluctuations 2005]

... and the experimental data



A predicted large suppression of the net-charge fluctuations is not observed!

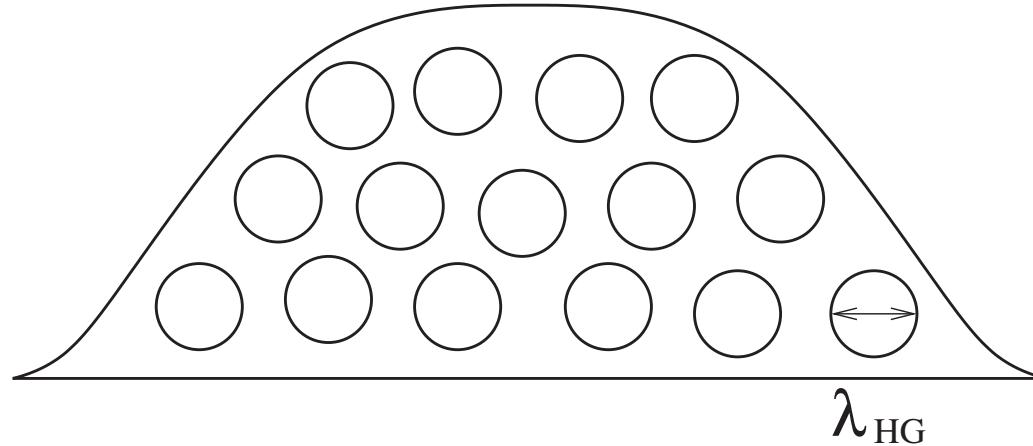
# Why not?

- The hadronic phase following the QGP phase could have been long (enough).
- Only a fraction of the charged particles may **remember** their QGP origin.
- Need **LOCAL** observables.

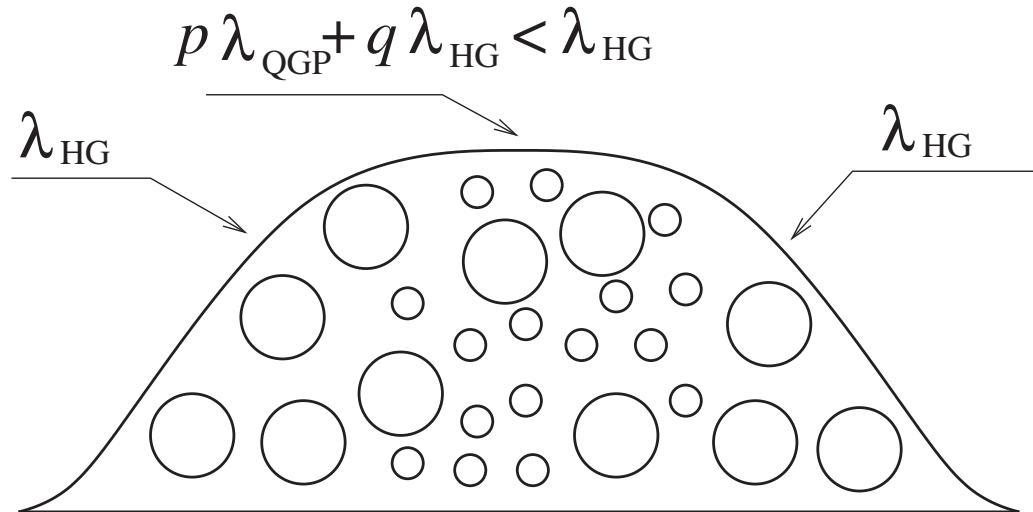
# Charge Transfer Fluctuations – Idea

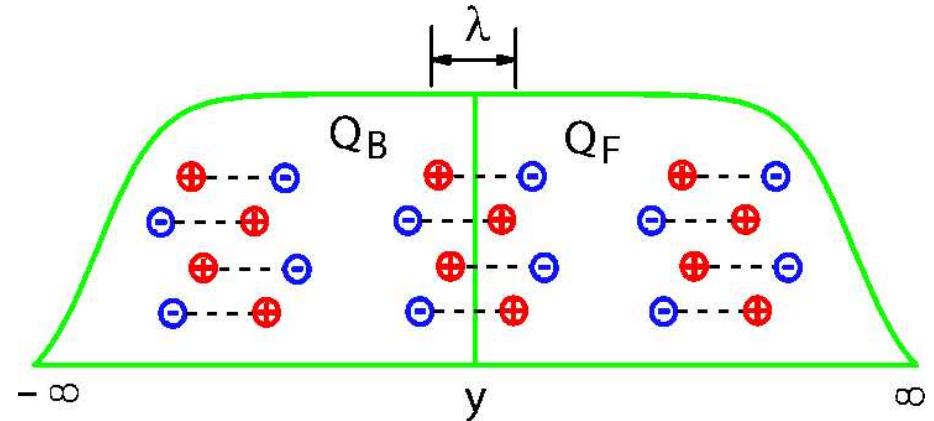
(SJ, L. Shi, M. Bleicher, PRC 73, 014905 (2006), PRC 72, 034904 (2005))

Hadron Gas only



Hadron Gas + QGP





- Observable:
  - \* Define:  $u(y) = [Q_F(y) - Q_B(y)]/2$
- Suppose a neutral cluster  $R$  decays near  $y$ .
  - \*  $R \rightarrow h^+ + h^-$  with a typical  $\Delta y = \lambda$
  - \* For each  $R$  decay,  $u(y)$  changes by  $\pm 1 \implies$  Random walk
  - \*  $D_u(y) = \langle \Delta u(y)^2 \rangle = N_{\text{steps}}(y) \approx \lambda \frac{dN_{\text{cluster}}}{dy}$
  - \* Since  $dN_{\text{cluster}}/dy \propto dN_{\text{ch}}/dy$ ,  $\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)$

# Charge Transfer Fluctuations

$$\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{Ch}}/dy} \propto \lambda(y)$$

Constant  $\kappa(y)$ : Thomas-Chao-Quigg Relationship

- Measure of the *local* charge correlation length

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[Net charge fluct. and Balance func : Averaged inside the obs. window]

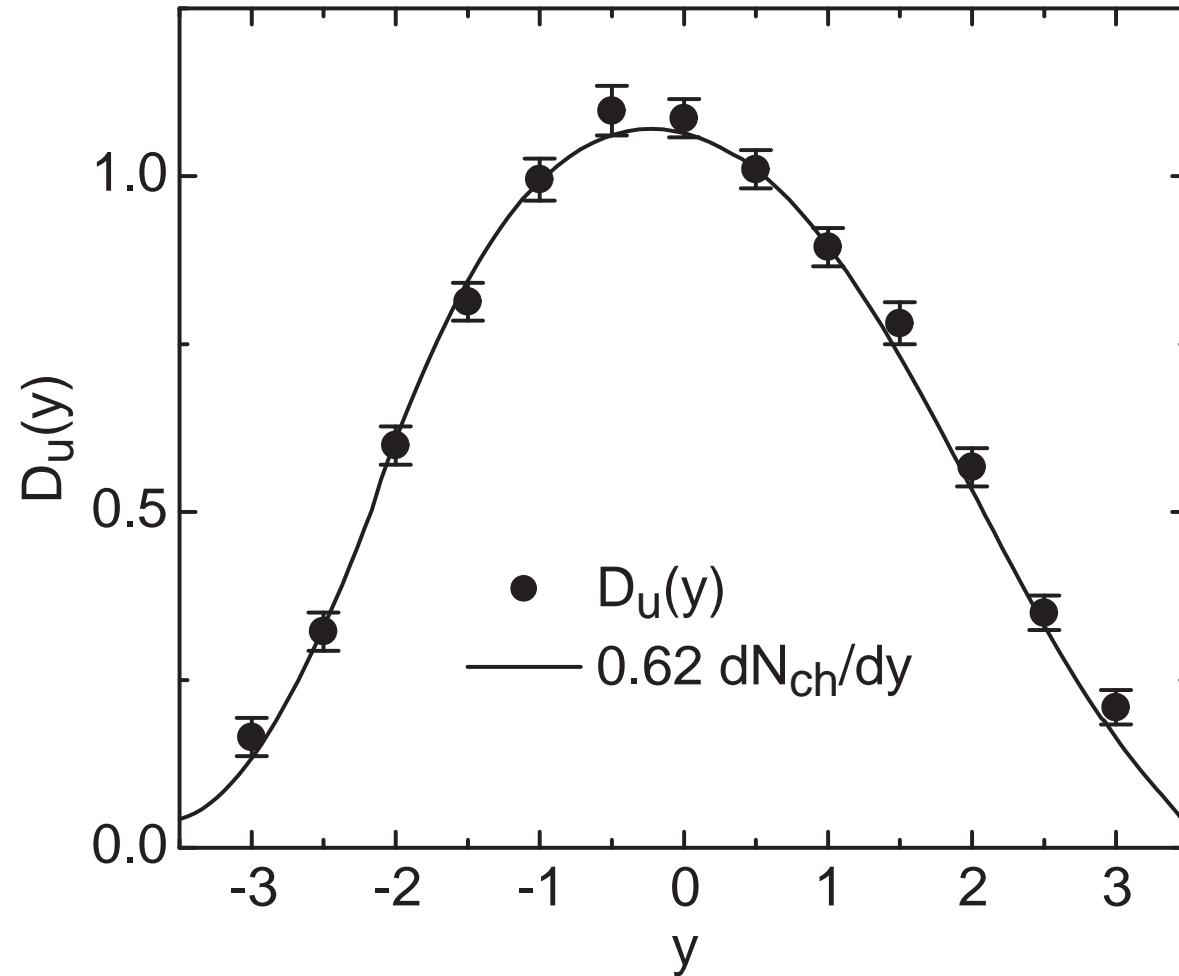
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- In elementary particle collisions,  $\kappa(y) \approx \text{const}$

*PP* ©  $p_{\text{max}} = 200 \text{ GeV}$



Kafka et.al. PRL 34, 687, 1975

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- If QGP has a much smaller  $\lambda$ , its presence should be reflected in  $\kappa(y) \implies$  Captures *inhomogeneity*.

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  - \*  $\kappa_{AA} < \kappa_{PP}$

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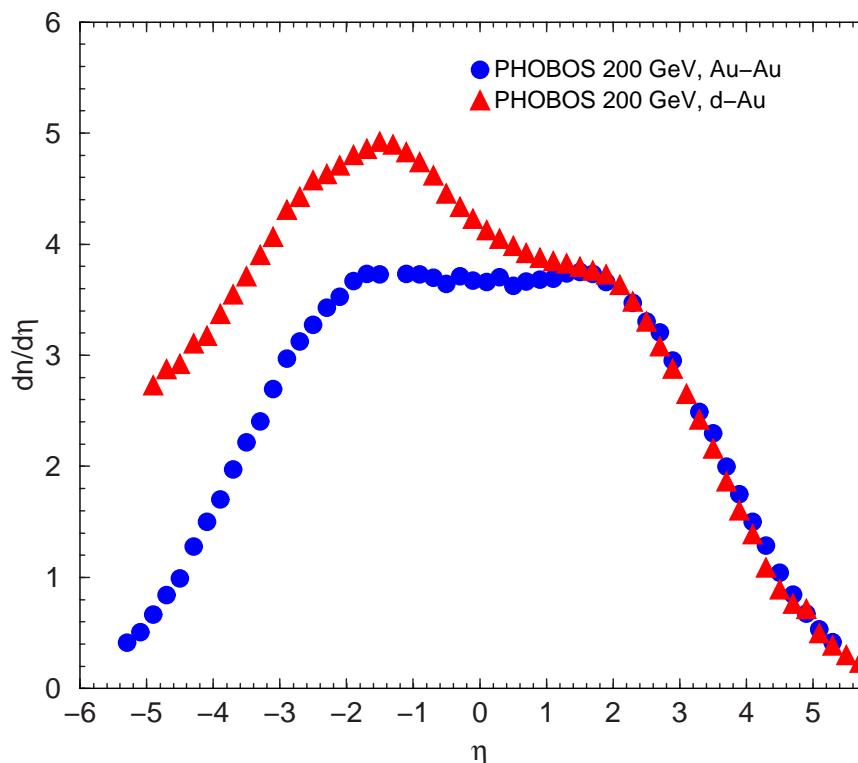
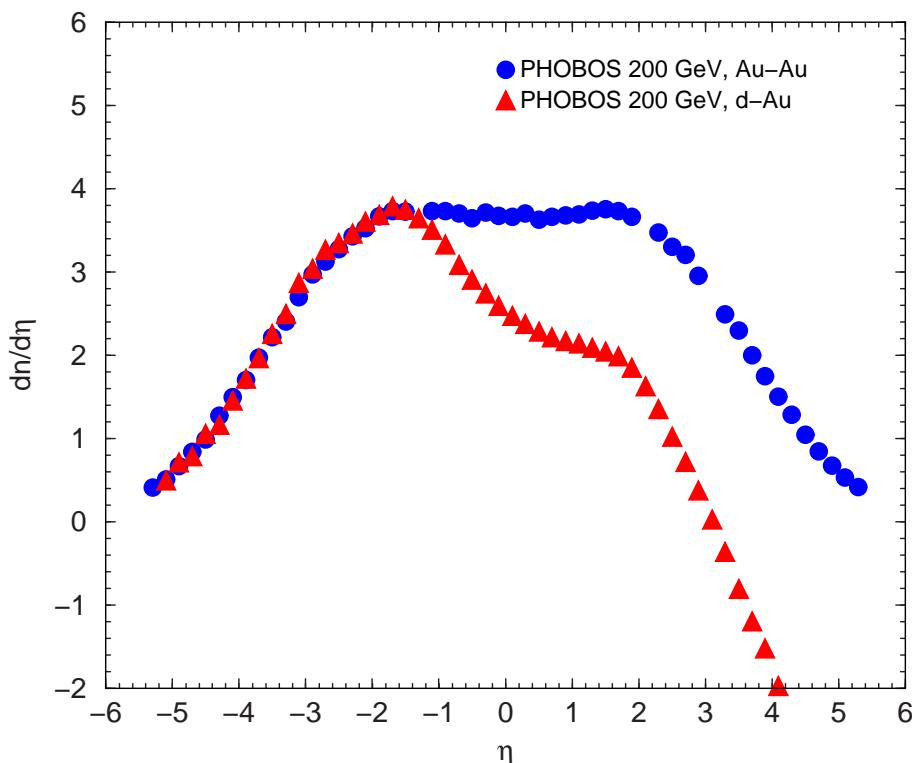
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- If QGP has a much smaller  $\lambda$ , its presence should be reflected in  $\kappa(y) \Rightarrow$  Captures *inhomogeneity*.
  - \*  $\kappa_{AA} < \kappa_{PP}$
  - \*  $\kappa_{AA}(y)$  : Significantly different from constant if QGP is made only locally

# How small is $\lambda_{QGP}/\lambda_{HG}$ ?

- $\langle \Delta Q^2 \rangle_{QGP} / \langle N_{ch} \rangle \approx (1/3) \langle \Delta Q^2 \rangle_{HG} / \langle N_{ch} \rangle$   
(Fractional charges + gluons)
- If neutral clusters, this implies  $\lambda_{QGP} \approx (1/3)\lambda_{HG}$

# Extent of QGP?

- Comparing d-Au and Au-Au  $dN/d\eta$  (Vertical scaling + small shifting (1 or 2 exp. bins))
- Same shapes outside the ‘plateau’! (Jeon, Bleicher, Topor Pop, Phys.Rev.C69:044904,2004, nucl-th/0309077)



# QGP vs. Hadron gas

- Color fluctuation: Hadrons are all color neutral  $\implies$  Difficult to observe color fluctuation
- Flavors are uncorrelated: No (quark) bound states to lock flavors together.
- Charge fluctuation: Quarks have fractional charges  $\implies$  Less charge fluctuation per charged degree of freedom
- There are gluons: Gluons contribute to the entropy but not to the charge fluctuation  $\implies$  Less charge fluctuation per charged degree of freedom

Sudden hadronization from QGP  $\implies$  Hadronic system rich in neutrals

# A Simple Neutral Cluster Model

[Similar to the old  $\rho, \omega$  model and Bialas et.al.'s Acta Phys. Polon. B6, 39, 1975 model]

- Make up an event with  $M_0$  positive particles and  $M_0$  negative particles by sampling

$$\rho(y_+, y_-) = R(y_+, y_- | Y) F(Y)$$

$M_0$  times for  $(+-)$  pairs.

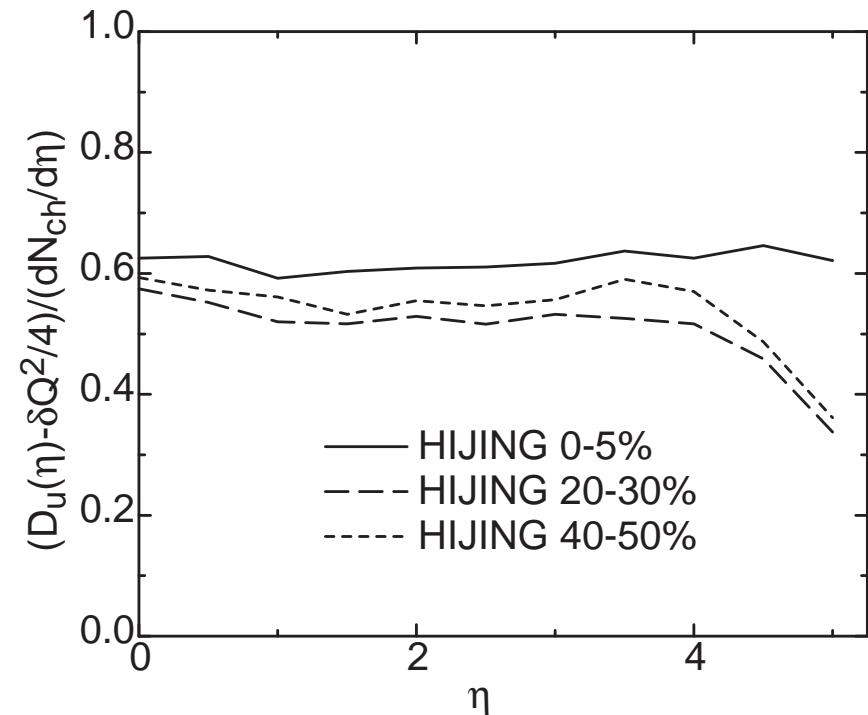
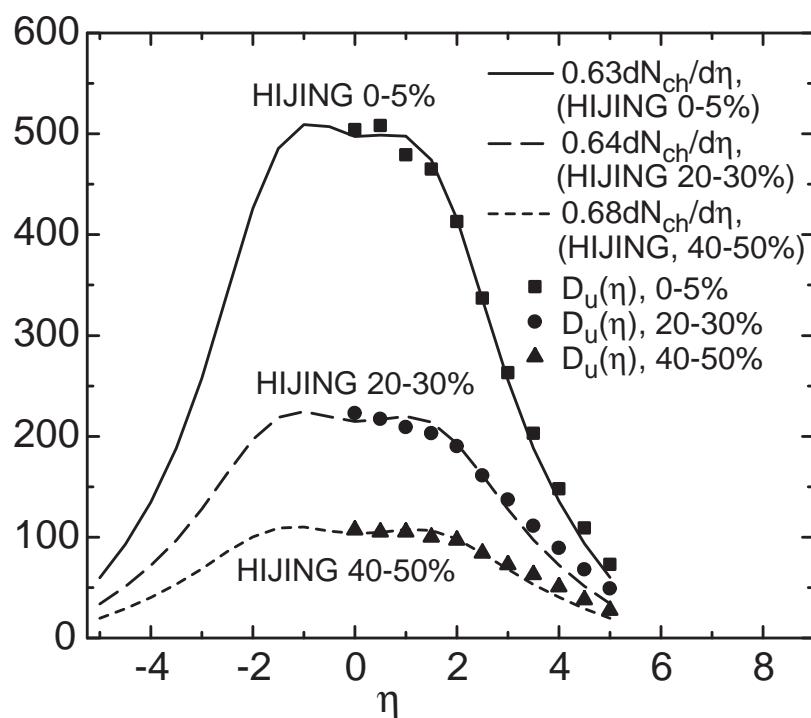
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$F(Y)$  : Cluster rapidity distribution,  $Y = (y_+ + y_-)/2$ .

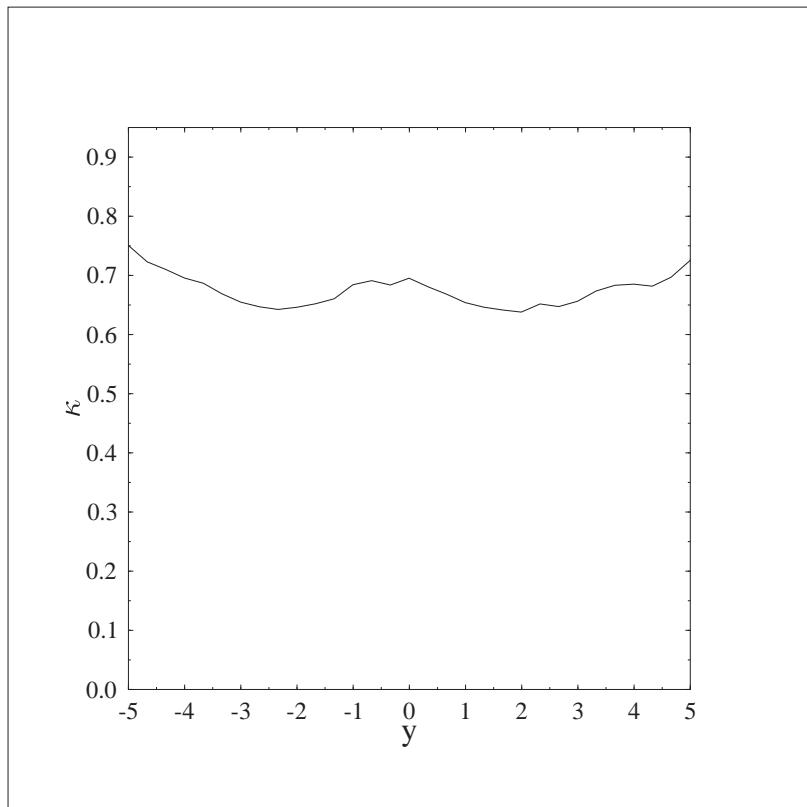
$R(y_+, y_- | Y)$  : Rapidity distribution of the daughters given  $Y$ .

# Single Component Model

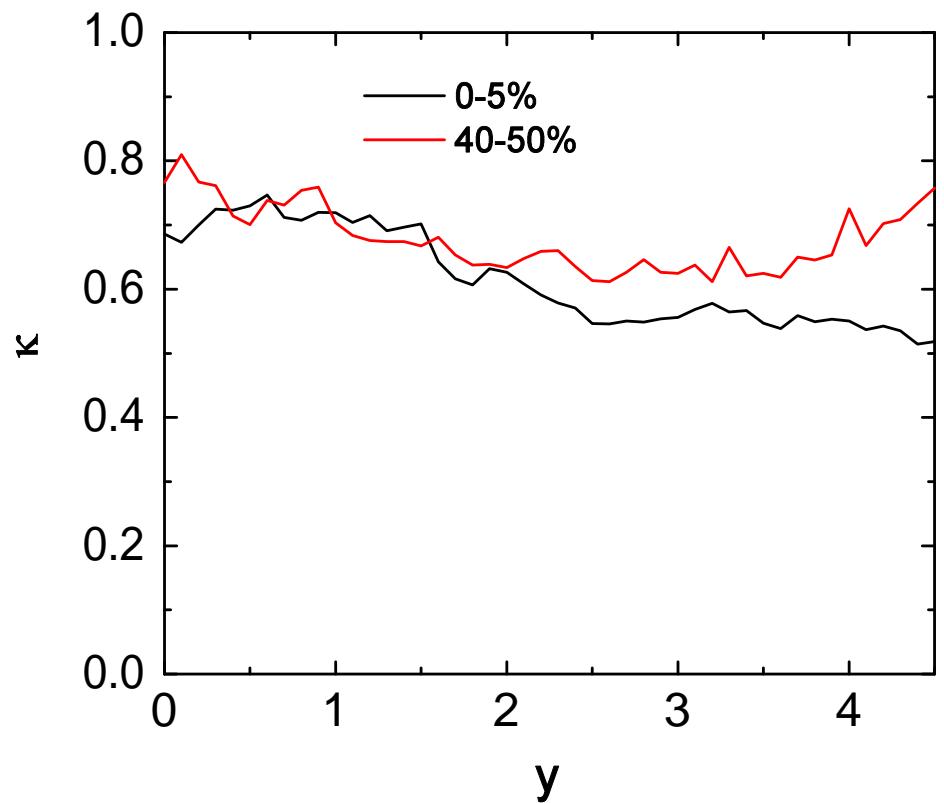
- $\rho(y_+, y_-) = \exp(-|\Delta y|/\lambda) F(Y)$  is an exact solution of the Thomas-Chao-Quigg relationship  $D_u(y) = \kappa dN_{\text{ch}}/dy$  with  $\lambda = 2\kappa$ .
- Hadronic models  $\Rightarrow$  constant  $\kappa$



# Cont.



UrQMD, Central 6 %



RQMD, Central, Semi-Peripheral

# Two Component Model

- Our model (L.Shi, S.Jeon):

Two species of neutral clusters  
( $\sim$  Hadronic + QGP):

Sample

$$\rho_H(y_+, y_-)$$

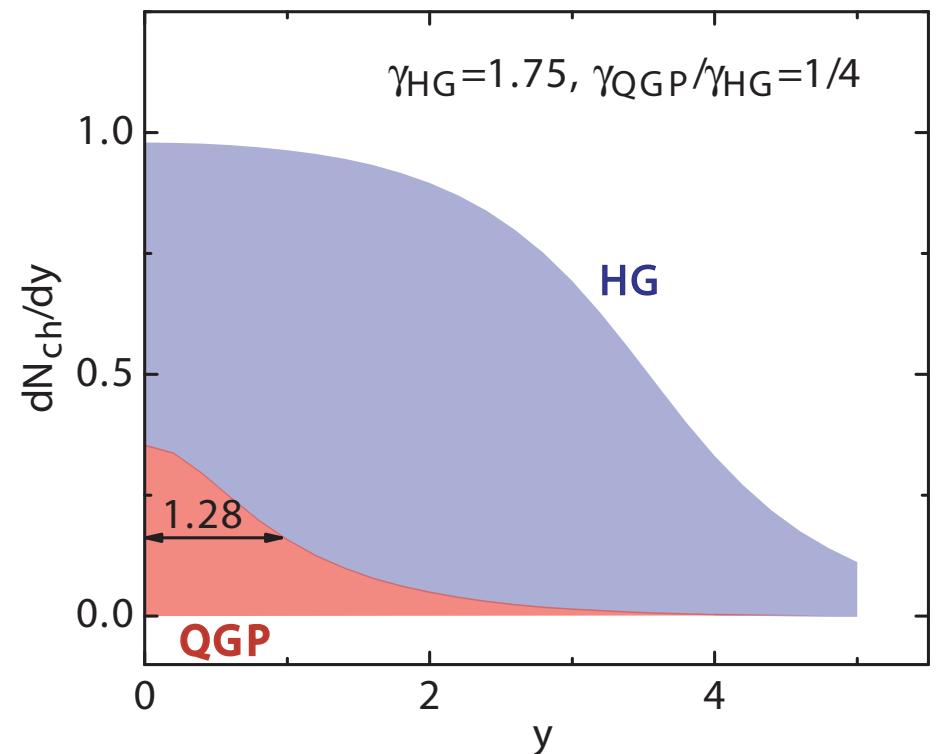
$$= R_H(y_+ - y_- | Y) F_H(Y)$$

and

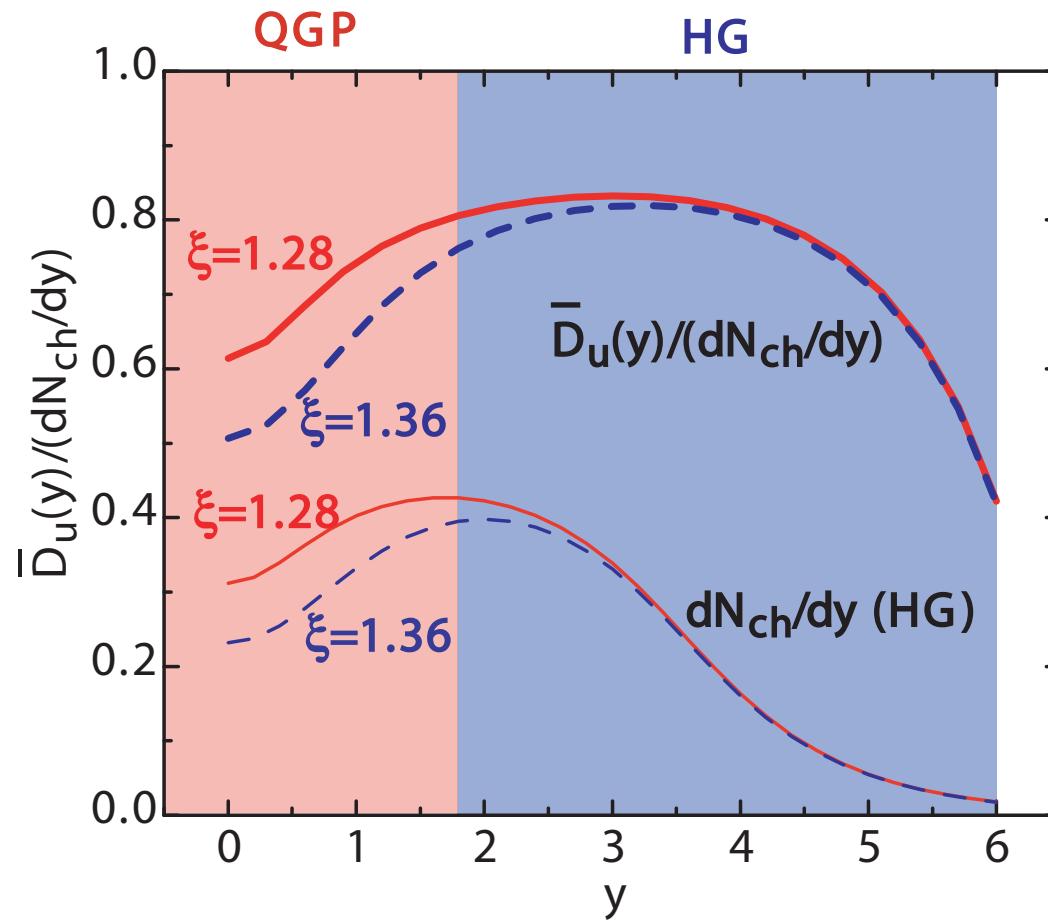
$$\rho_{QGP}(y_+, y_-)$$

$$= R_{QGP}(y_+ - y_- | Y) F_{QGP}(Y)$$

$$\text{with } \lambda_{QGP} \approx (1/4)\lambda_H$$



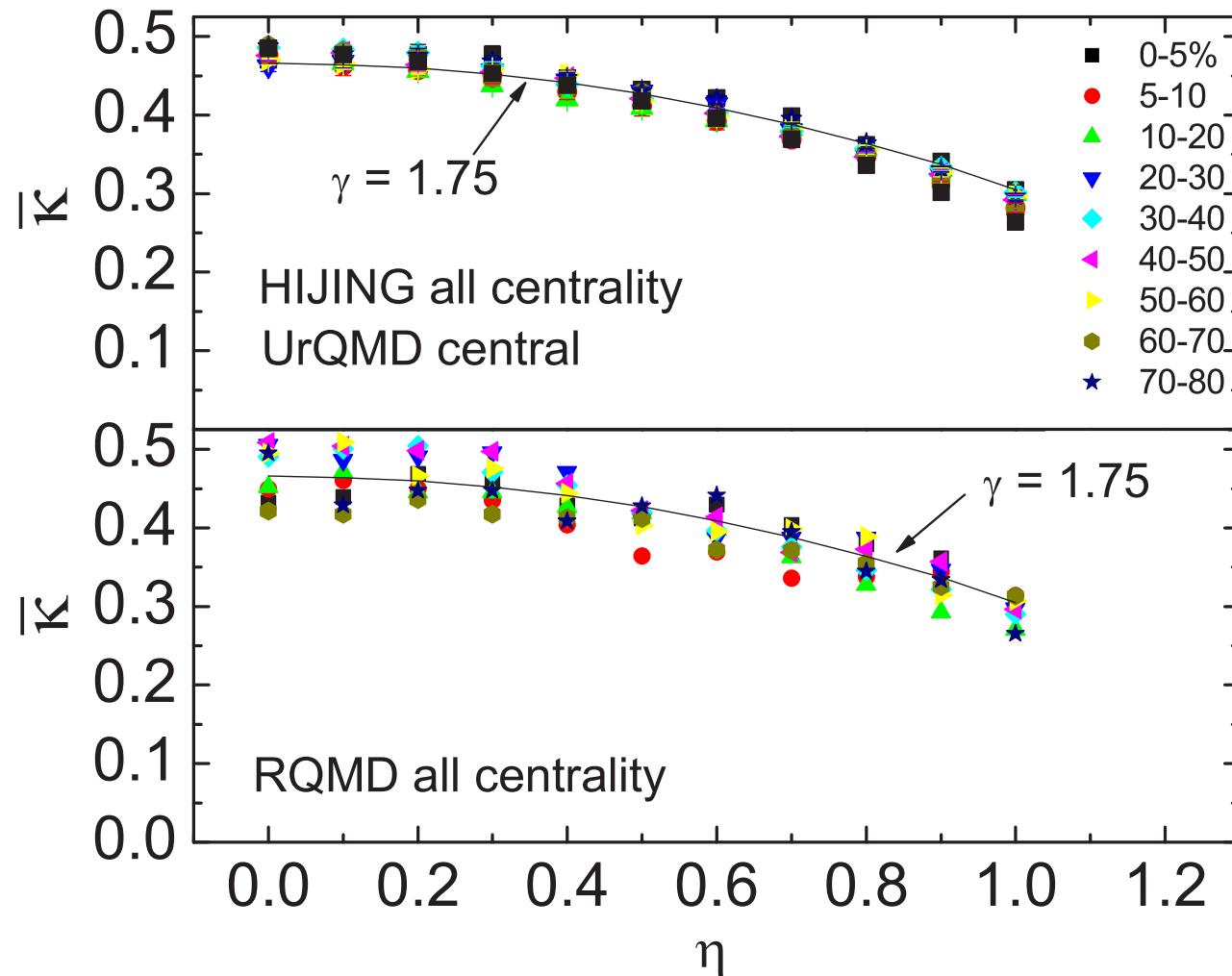
# HG + QGP – Full $\eta$ space



$$\kappa(\eta) = \frac{\gamma_{HG}}{2} - \frac{\gamma_{QGP}}{2} \left( \frac{\gamma_{HG}}{\gamma_{QGP}} - 1 \right) \frac{dN_{QGP}/d\eta}{dN_{ch}/d\eta}$$

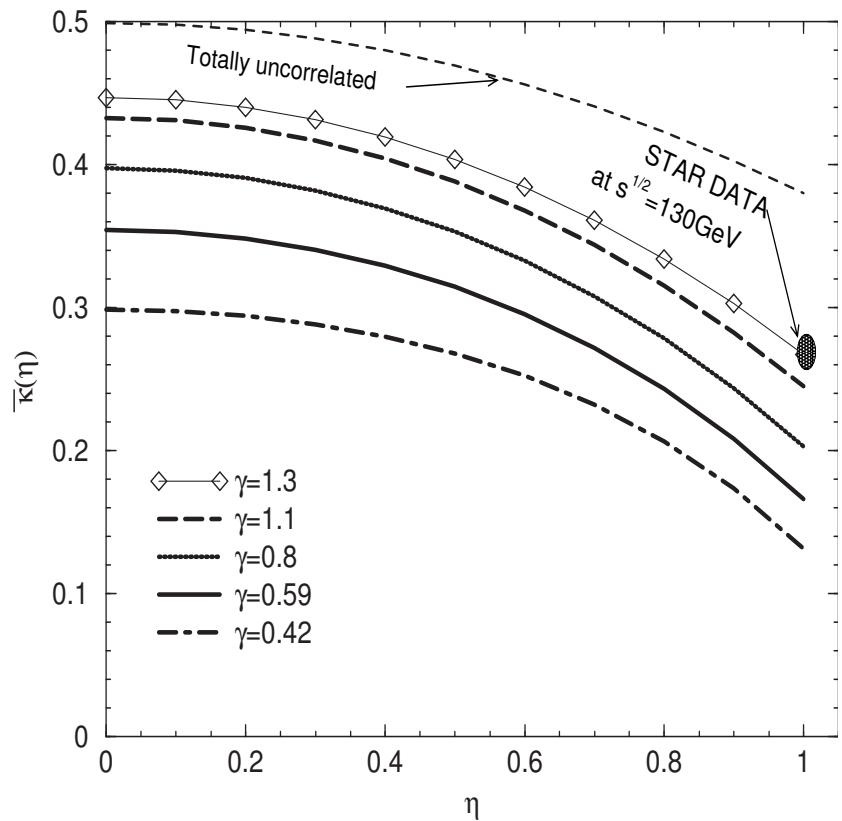
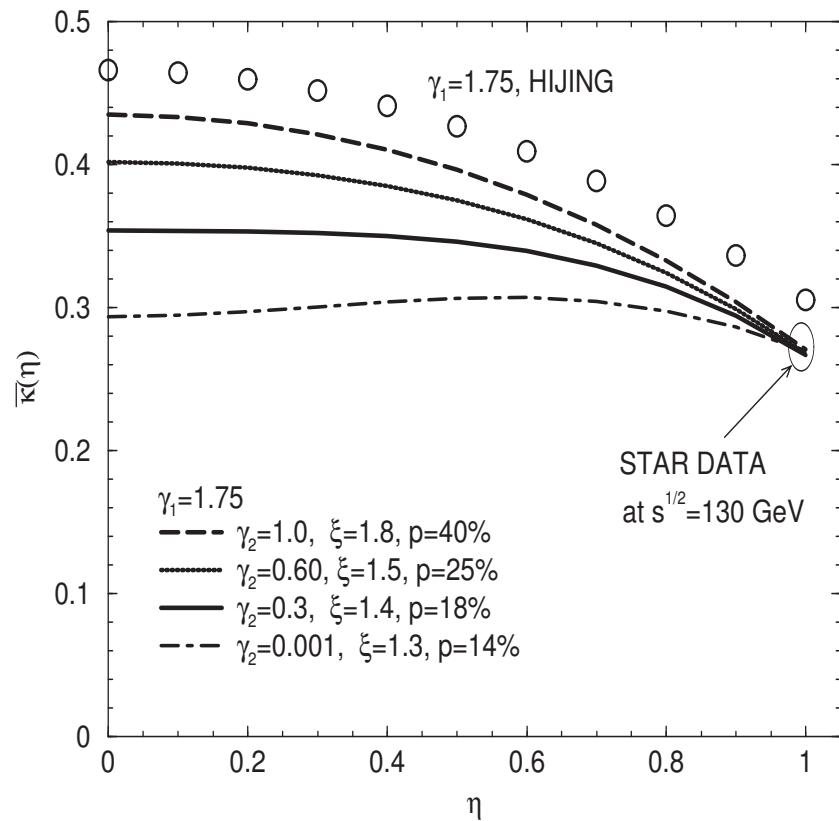
# HG – STAR acceptance

Hadronic models compared to single component results



# HG + QGP – STAR acceptance

End point fixed by  $\langle \Delta Q^2 \rangle / N_{\text{ch}}$



Left: 2-comp. results. Right: Single comp. results.

# Conclusions

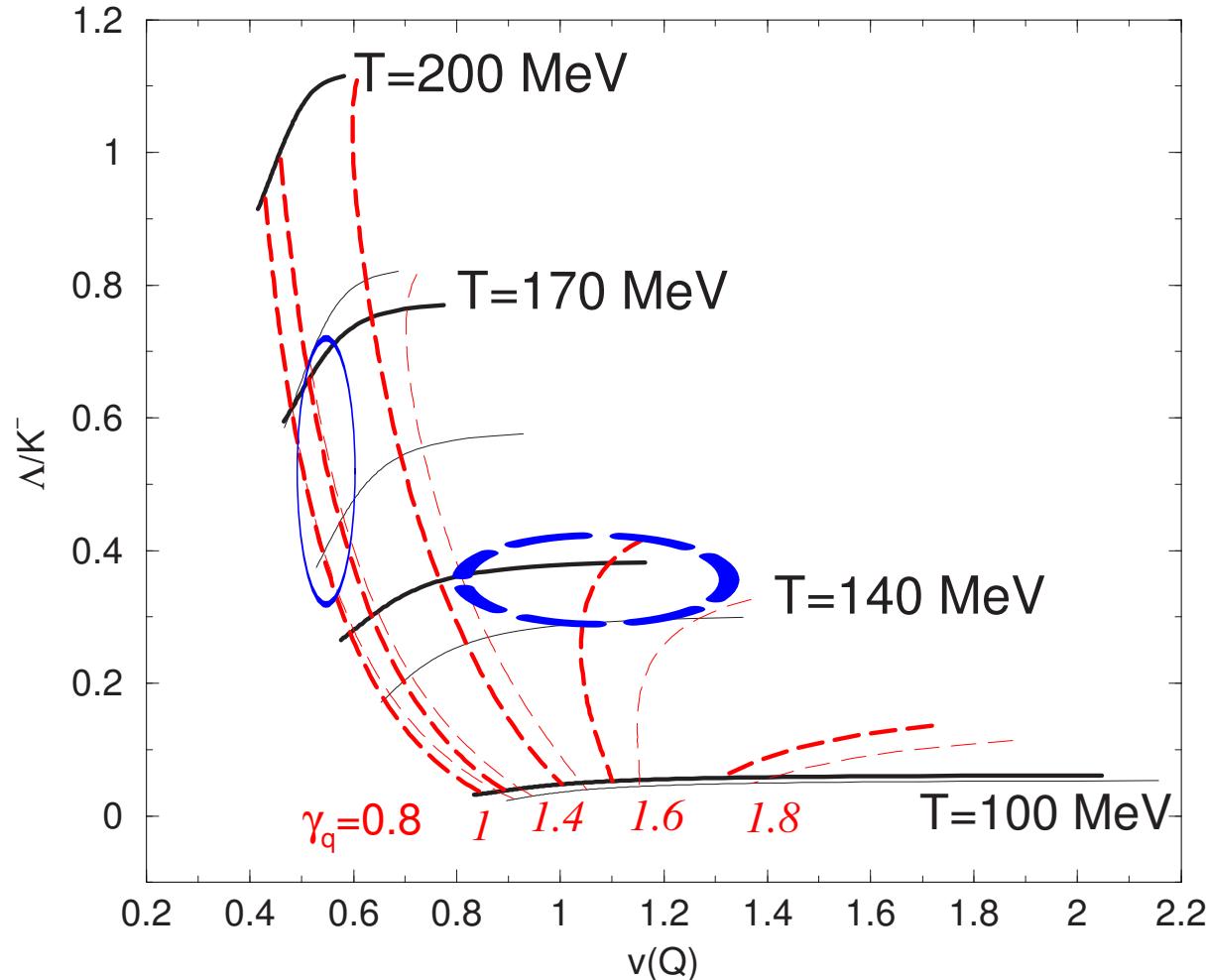
- Charge fluctuations: Some setbacks, but still a promising probe.
- Need **local** observables.
- Charge transfer:  $u(y) = (Q_F(y) - Q_B(y))/2$
- $\kappa(y) \equiv \langle \Delta u(y)^2 \rangle / dN_{\text{ch}}/dy$ : A measure of **local** charge correlation length  $\implies$  Captures **inhomogeneity**

- QGP may be created in a small region around midrapidity.  
As collisions become more central
  - \* Large acceptance:  $\kappa(y)$  develops a dip in the middle
  - \* Small acceptance:  $\kappa(0)$  becomes smaller faster than  
 $\kappa(y_0) \implies$ Flattening
- May explain why the net charge fluctuations do not show the expected drop.
- Correlate, correlate, ...

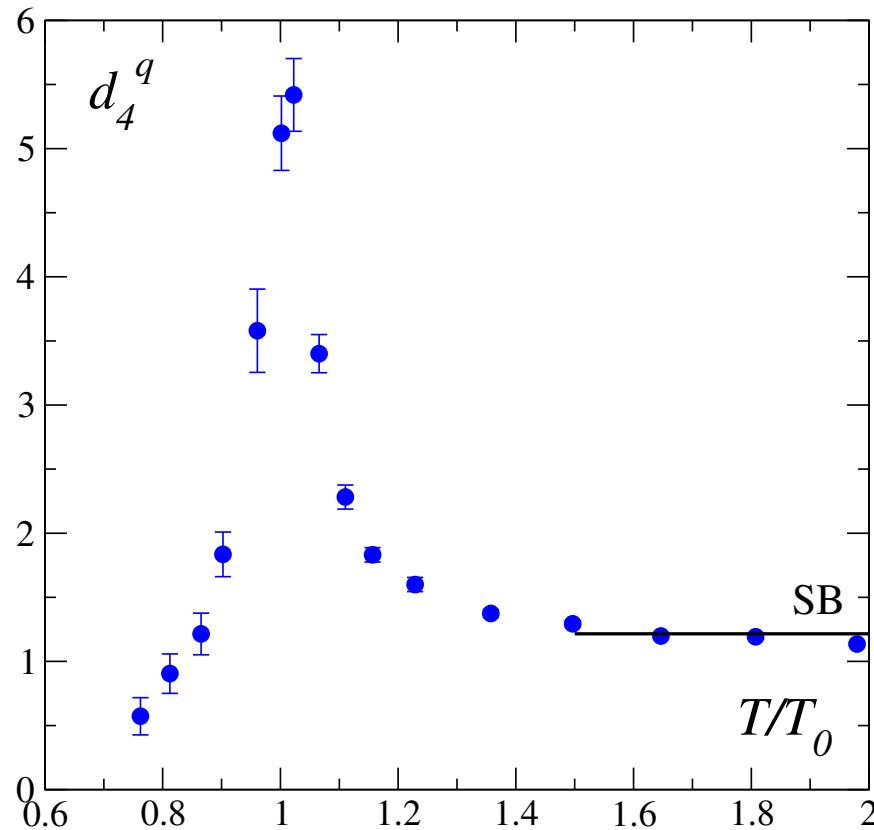
# Correlate, correlate ...

(Remember the Elephant)

[G.Torrieri, SJ, J. Rafelski, arXiv:nucl-th/0503026, To appear in PRC.]



# Food for thoughts ...



The 4-th cumulant of the quark number distribution.

S.Ejiri, F.Karsch and K.Redlich, PLB 633:275-282, 2006

# Thanks

RIKEN-BNL

RIKEN Japan

BNL Nuclear Theory

Rae Greenberg

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Pam Esposito

Nick Samios

Tammy Stein

Tony Baltz

Taeko Ito

Larry McLerran

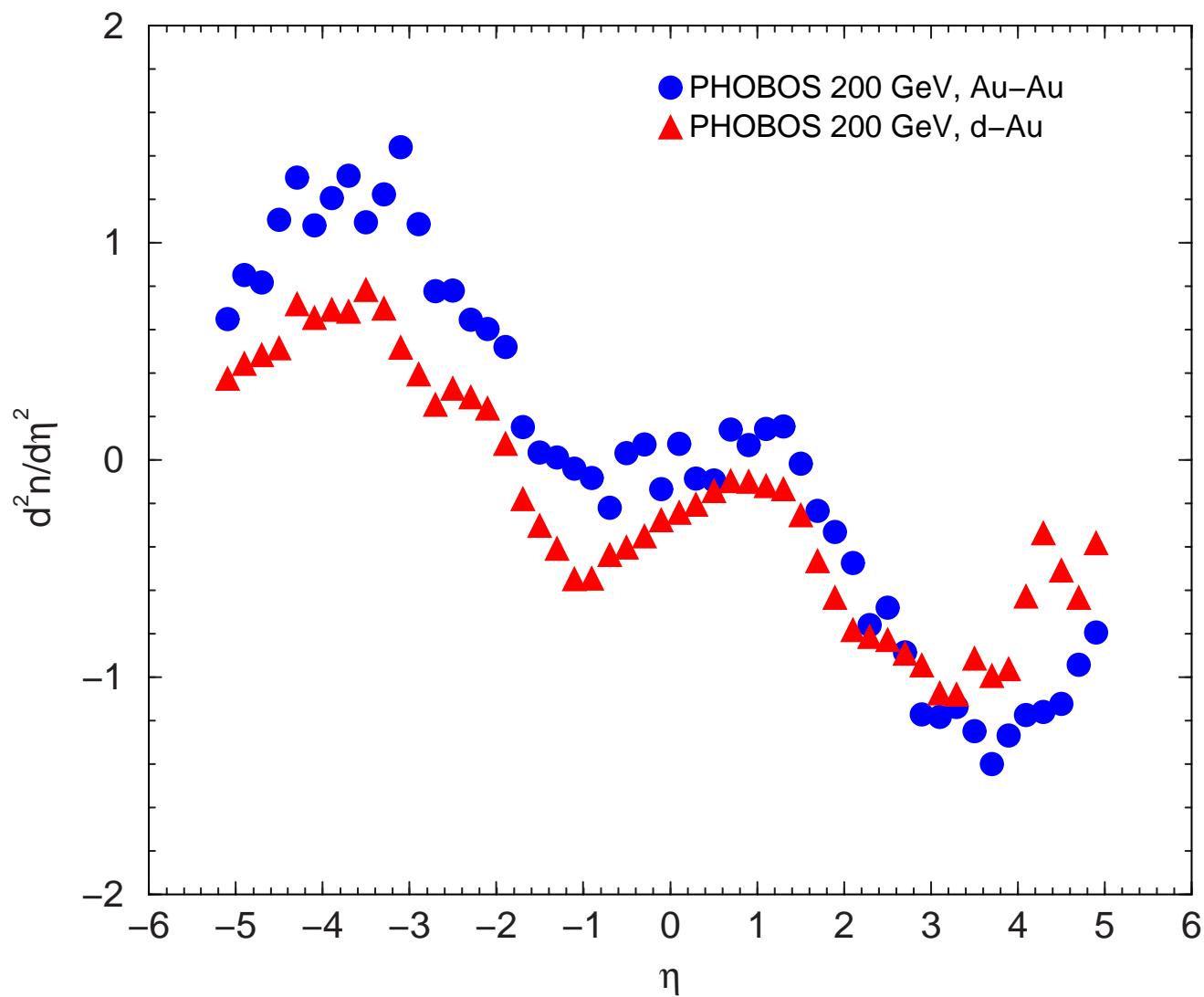
Marcy Chaloupka

Shigemi Ohta

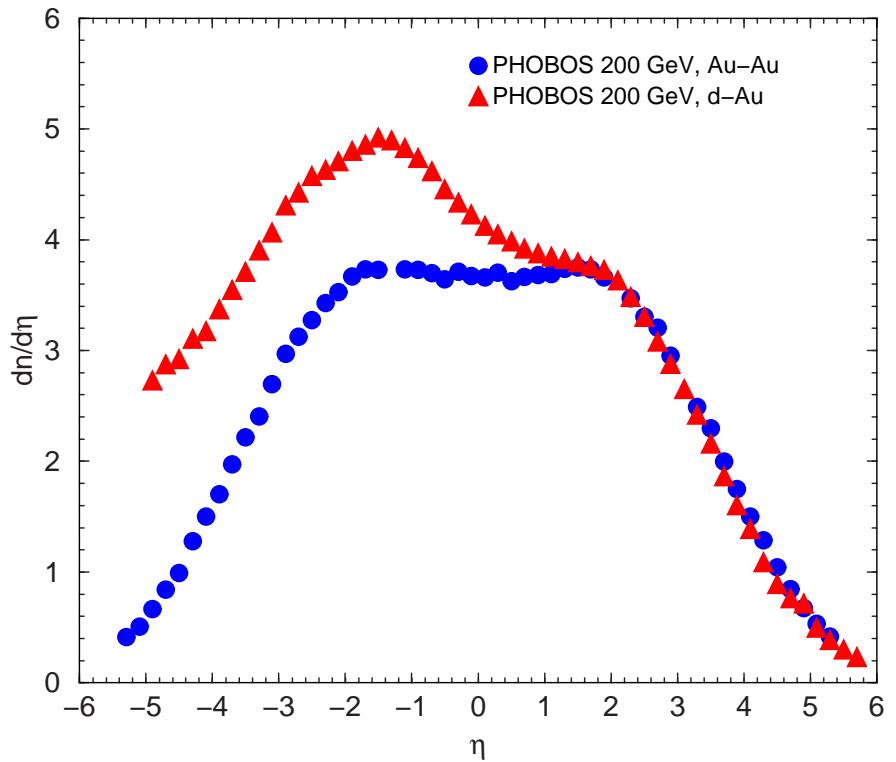
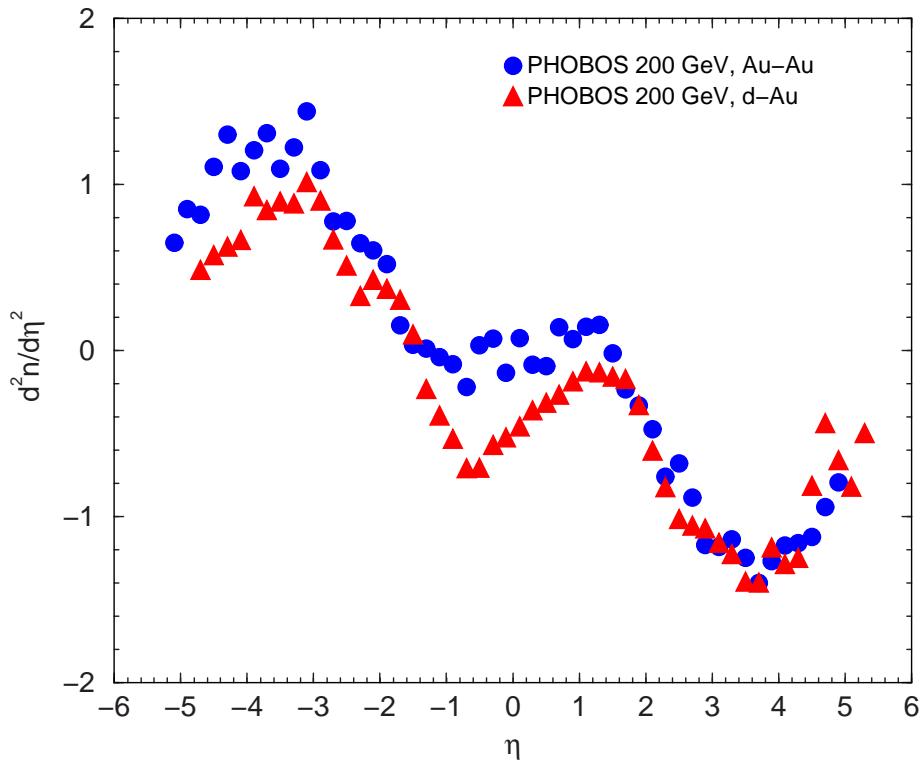
Fellow RIKEN fellows

# Backup slides

dAu

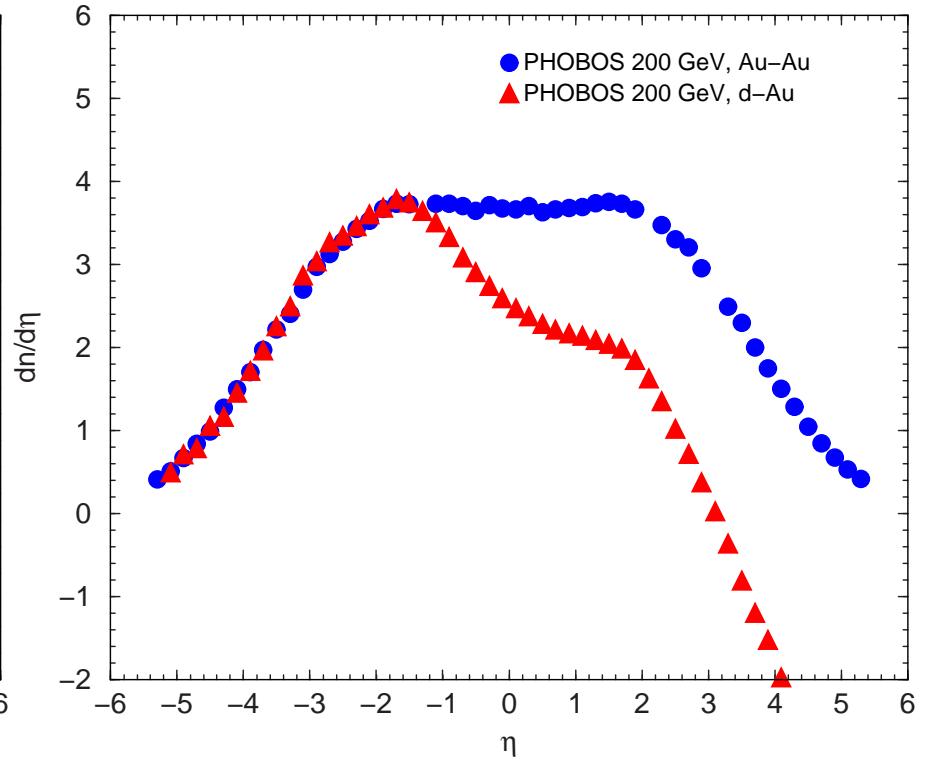
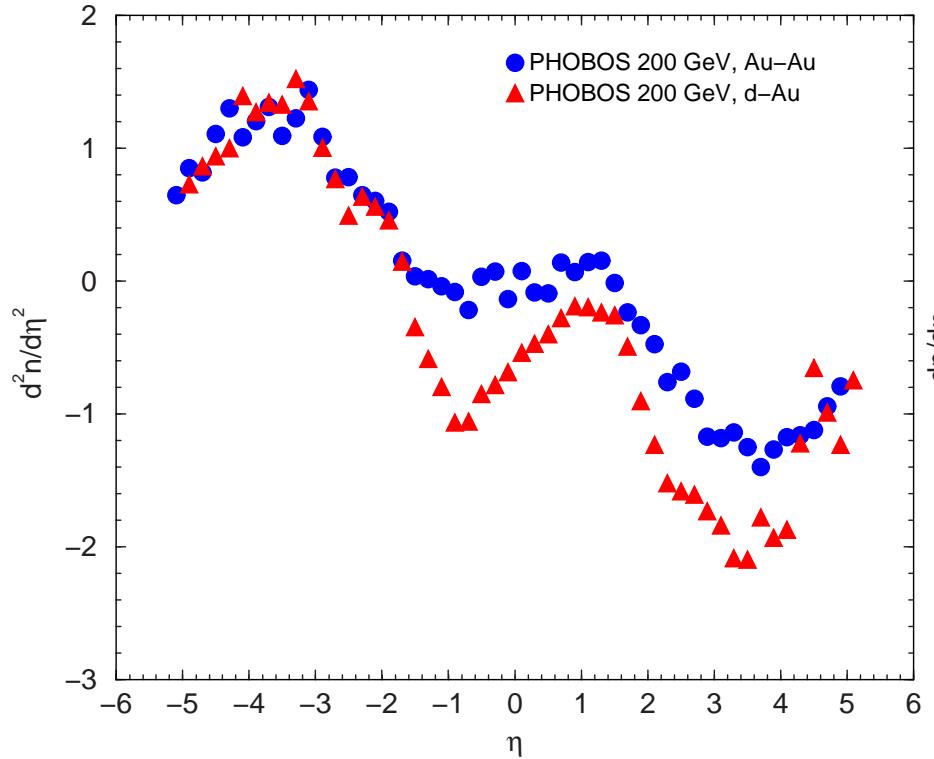


# d side



- Vertical scaling:  $\times 1.3$
- Horizontal shifting:  $+ 0.4$  (2 experimental bins)

# Au side



- Vertical scaling:  $\times 1.3 \times 1.5$
- Horizontal shifting:  $+ 0.2$  (1 experimental bin)

# Modeling

“Correlation function has all the information.”

True. Any charge fluctuation observable measures a particular aspect of  $C_Q(y, y') = C_{++}(y, y') + C_{++}(y, y') - 2C_{+-}(y, y')$  where  $C_{ab}(y, y') = \frac{dN_{ab}}{dy dy'} - \frac{dN_a}{dy} \frac{dN_b}{dy'}$

- Different fluctuations emphasize different aspects of correlation.
- Fluctuations allow physical interpretation of the features through model studies.

# Correlations

- Relevant to fluctuations: Single particle distributions and 2-particle correlation functions.
- Single particle distribution functions :  
 $\rho_\alpha(p)dp$  = Average number of  $\alpha$  within  $dp$  around  $p$ .

$$\int_{\Delta\eta} dp \rho_\alpha(p) = \langle N_\alpha \rangle_{\Delta\eta}$$

- 2-particle correlation functions :  
 $\rho_{\alpha\beta}(p_1, p_2) dp_1 dp_2$  = Average number of  $\alpha\beta$  pairs within  $dp_1 dp_2$  around  $p_1, p_2$

$$\int_{\Delta\eta} dp_1 dp_2 \rho_{\alpha\beta}(p_1, p_2) = \langle N_\alpha N_\beta \rangle_{\Delta\eta} - \delta_{\alpha\beta} \langle N_\alpha \rangle_{\Delta\eta}$$

# A toy model – “ $\rho$ ” gas

- $M_{\pm}$  independently emitted  $\pm$  particles “ $\rho^{\pm}$ ”  $\implies g_{\pm}(p_{\pm})$
- $M_0$  neutral clusters “ $\rho^0$ ”  $\implies f_0(p_+, p_-)$ ,  $g_0(p) = \int dq f_0(p, q)$ 
  - \* Single particle distributions

$$\rho_{\pm}(p) = \langle M+ \rangle g_{\pm}(p) + \langle M_0 \rangle g_0(p)$$

- Two particle correlation functions

$$\begin{aligned}
 C_{++}(p_1, p_2) &\equiv \rho_{++}(p_1, p_2) - \rho_+(p_1)\rho_+(p_2) \\
 &= \sum_{a=+, 0} \sum_{b=+, 0} \langle \delta M_a \delta M_b \rangle g_a(p_1)g_b(p_2) \\
 &\quad - \langle M_+ \rangle g_+(p_1)g_+(p_2) - \langle M_0 \rangle g_0(p_1)g_0(p_2)
 \end{aligned}$$

$$\begin{aligned}
 C_{+-}(p_1, p_2) &= \sum_{a=+, 0} \sum_{b=-, 0} \langle \delta M_a \delta M_b \rangle g_a(p_1)g_b(p_2) \\
 &\quad + \langle M_0 \rangle [f_0(p_1, p_2) - g_0(p_1)g_0(p_2)]
 \end{aligned}$$

If Poisson-like, all terms in  $C_{\alpha\beta}$  are  $O(M)$ .

In  $\rho_{\alpha\beta}$ , the leading term is  $O(M^2) \implies f_0$  is hidden.

# Free gas estimates

For QGP,

$$\langle \Delta Q^2 \rangle \approx \left[ \frac{1}{9} \langle N_{d+\bar{d}} \rangle + \frac{4}{9} \langle N_{u+\bar{u}} \rangle \right]$$

$$S \approx 4 \left( \langle N_g \rangle + \langle N_{u+\bar{u}} \rangle + \langle N_{d+\bar{d}} \rangle \right)$$

For  $\pi$  gas,

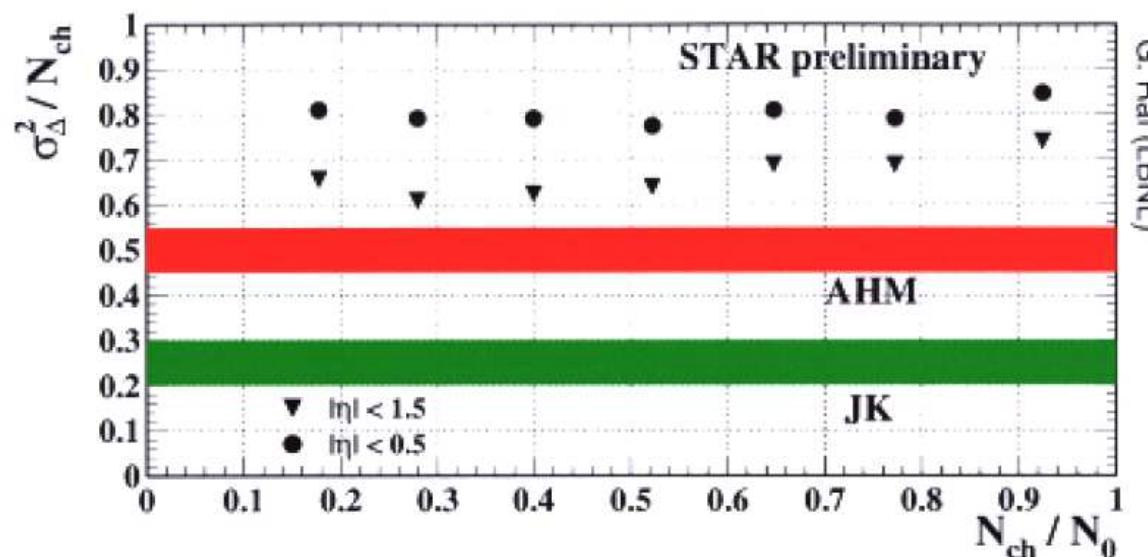
$$\langle \Delta Q^2 \rangle \approx \left[ \langle N_{\pi^+} \rangle + \langle N_{\pi^-} \rangle \right]$$

$$S \approx 4 \left( \langle N_{\pi^+} \rangle + \langle N_{\pi^-} \rangle + \langle N_{\pi^0} \rangle \right)$$

Difference:  $(\langle \Delta Q^2 \rangle / S)_{QGP} / (\langle \Delta Q^2 \rangle / S)_{\pi} \approx 1/4$

# Data – J.Reid, QM 2001

## $N_+, N_-$ Fluctuations - Centrality Dependence

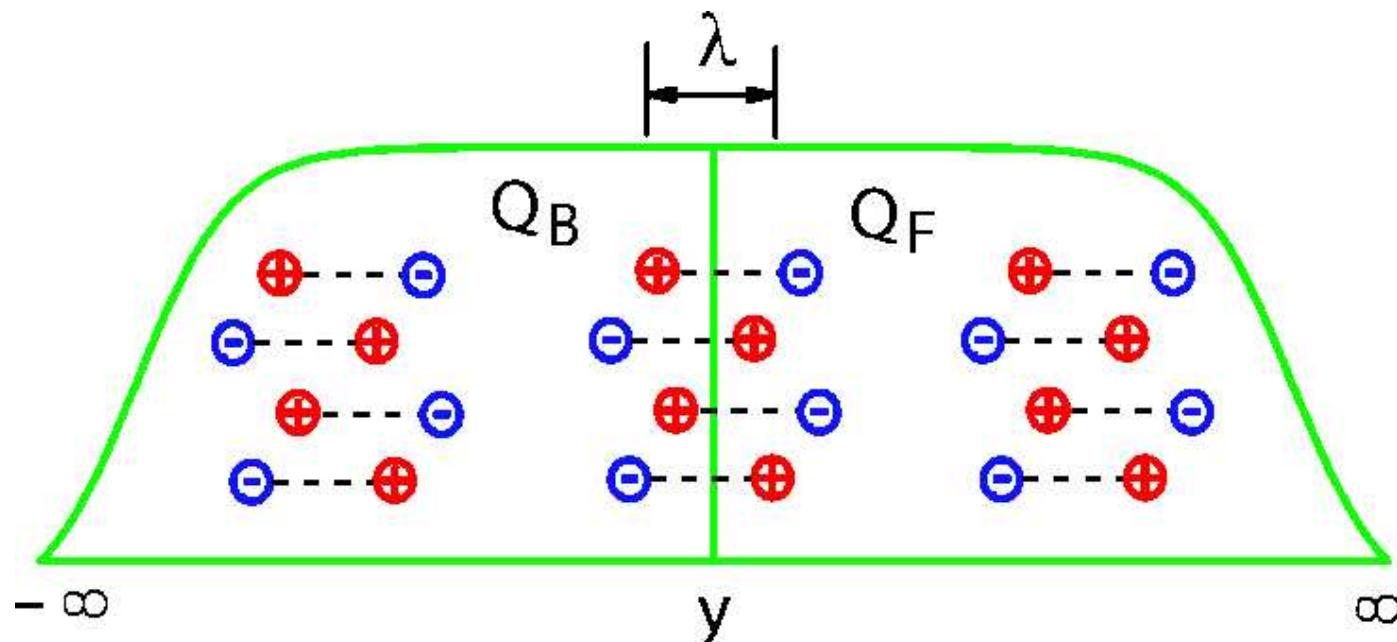


- Charge-ratio studies provide  $\sigma_{\Delta}^2$  for central events:  $0.75-0.85 N_{ch}$
- Small centrality dependence in minbias analysis
- Deviations from unity consistent with resonance correlations
- Expected dependence on  $\eta$  acceptance
- Multiplicity fluctuations: agreement between SPS\* and RHIC

\* NA49 EbyE Fluctuations poster - QM2001 session A: P082

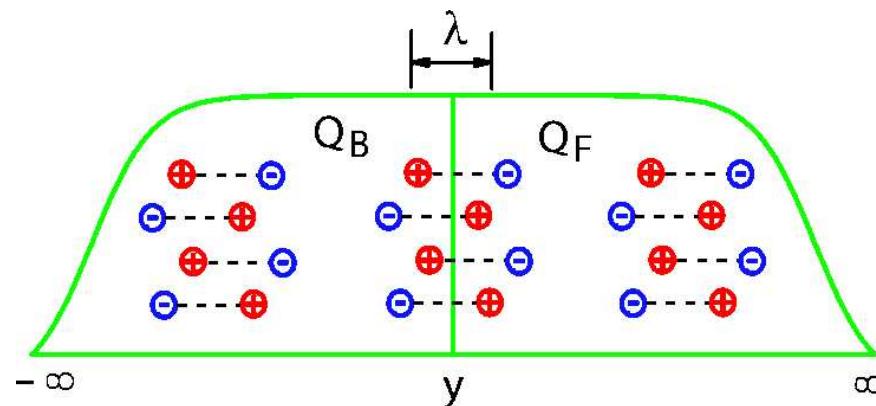
(Thomas, Quigg, Chao (1973), Shi, Jeon, hep-ph/0503085)

- Charge Transfer:  $u(y) = [Q_F(y) - Q_B(y)] / 2$  where
  - $Q_F(y)$  = Net charge in the forward region of  $y$
  - $Q_B(y)$  = Net charge in the backward region of  $y$



- $u(y) = [Q_F(y) - Q_B(y)] / 2$
- Suppose a neutral cluster  $R$  decays near  $y$ .
  - \*  $R \rightarrow h^+ + h^-$  with a typical  $\Delta y = \lambda$
  - \* For each  $R$  decay,  $u(y)$  changes by  $\pm 1 \implies$  Random walk
  - \*  $D_u(y) = \langle \Delta u(y)^2 \rangle = N_{\text{steps}}(y) \approx \lambda \frac{dN_{\text{cluster}}}{dy}$
  - \* Since  $dN_{\text{cluster}}/dy \propto dN_{\text{ch}}/dy$ ,

$$\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)$$



# Models

- Different choices of  $R$  and  $F \implies$ Different Models
- For instance, Bialas et.al.'s model is equivalent to sampling  $\rho_{75}(y_+, y_-) = f(y_+|Y)f(y_-|Y)F(Y)$  Correlation provided by integration over  $Y$ .
- Our model: Two different scenarios
  - \* Single species of neutral clusters ( $\sim$  Hadronic): Sample

$$\rho(y_+, y_-) = R(y_+ - y_-|Y)F(Y)$$

where ( $M_\pm = 0$ )

$$F(Y) = \text{Wood-Saxon}$$

$$R(y|Y) = C \exp(-|y|/\lambda)$$

Or

$$R(y|Y) = C' \exp\left(-y^2/2\sigma^2\right)$$

Explicit charge correlation with const.  $\lambda$  or  $\sigma$

# Models – Cont.

- Single component model:  $D_u(y) = \kappa dN/dy$  means
$$\int_{-\infty}^y dy' \int_y^\infty dy'' f_0(y', y'') = \kappa \int_{-\infty}^\infty dy' f_0(y, y')$$
Solutions in two extreme cases:
  - \* Indenpendent (no cluster) :  $f_0(y, y') = g(y)g(y'')$ 
$$g(y) = \frac{1}{4\kappa} \frac{1}{\cosh^2(y/2\kappa)} \propto \frac{dN}{dy}$$
  $\implies$  Does not correspond to real spectra.
  - \* 2 particle cluster:  $f_0(y, y') = R(y_{\text{rel}})F(Y)$  with  
 $y_{\text{rel}} = y - y'$  and  $Y = (y + y')/2$ 
$$f_0(y, y') = \frac{1}{4\kappa} \exp\left(-\frac{|y_{\text{rel}}|}{2\kappa}\right) F(Y)$$

# Charge difference $\eta, \phi$ correlations:

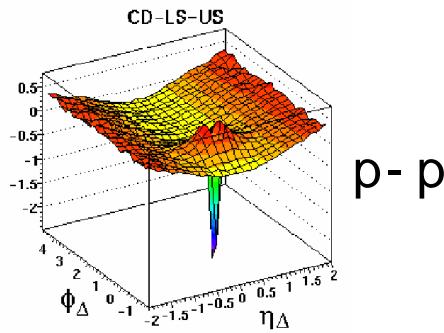
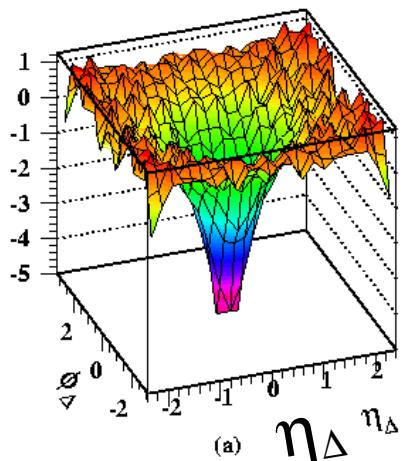
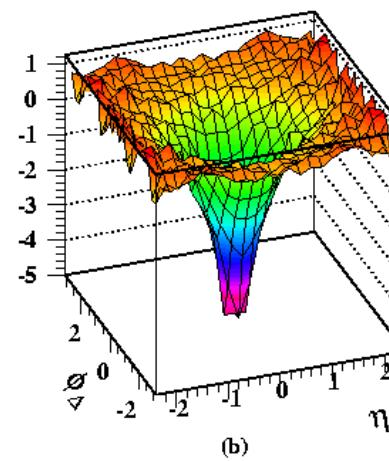
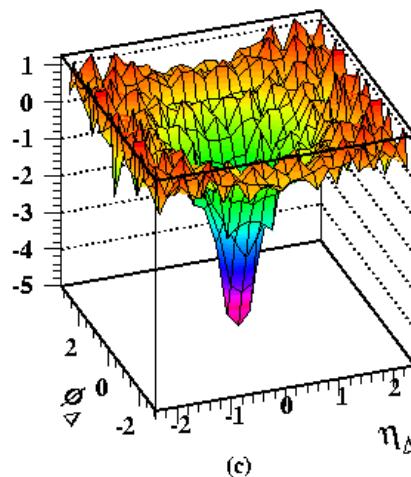
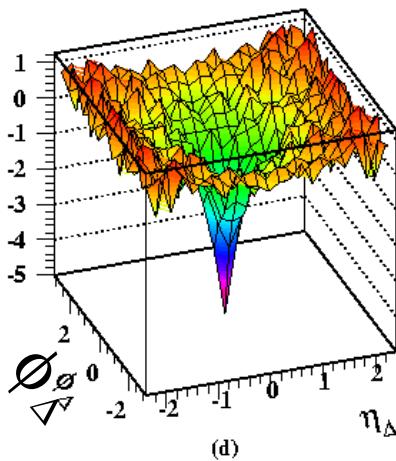
Au- Au 130 GeV Like- Unlike Charge Difference

Lanny Ray, Corr & Fluct in RNC 2005  
Is the medium partonic or hadronic?

peripheral



central



STAR preliminary

05/09/05

Correlations & Fluctuations at  
MIT

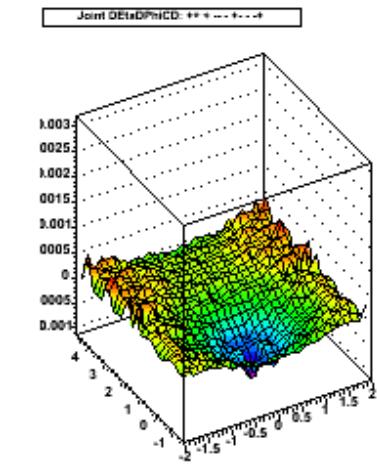
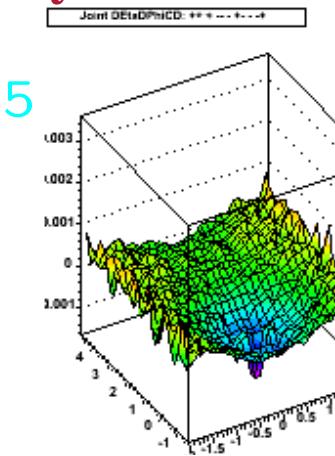
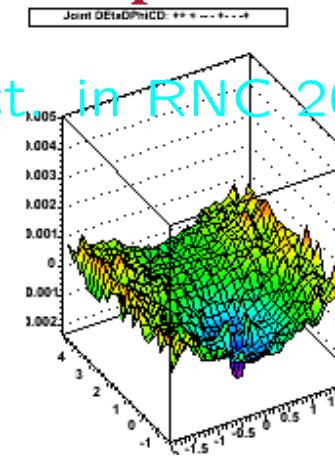
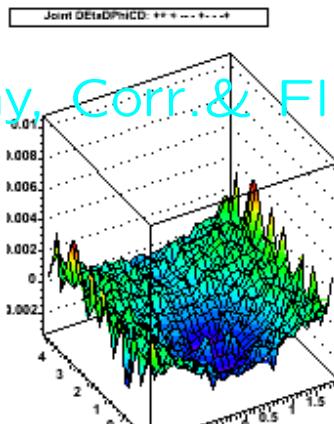
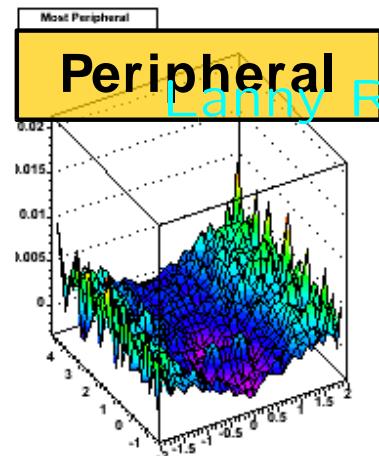
*J. Adams et al. (STAR),  
nucl-ex/0406035.*

Development of 2D symmetric correlation shape and increased amplitude.

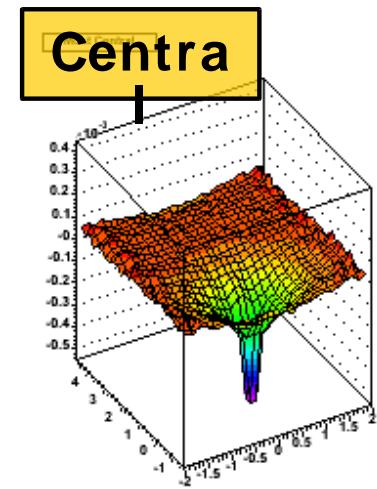
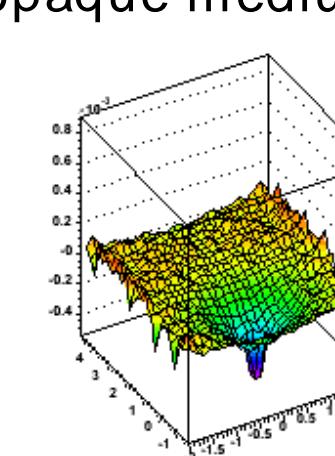
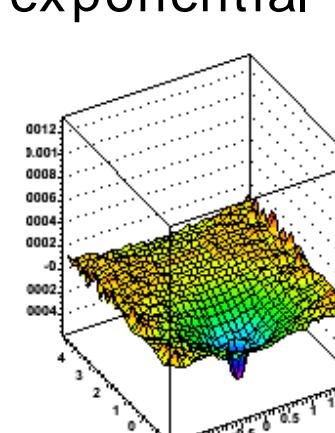
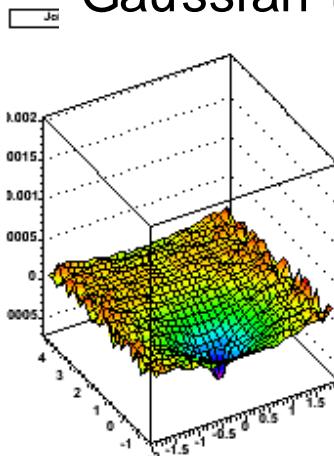
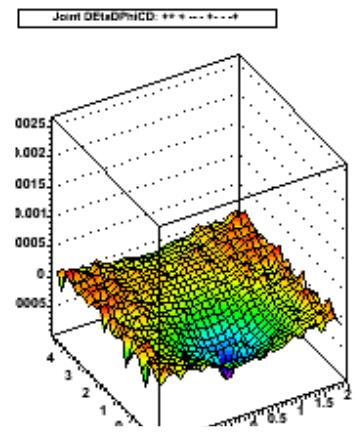
~ 300k events  
 $0.15 < p_t < 2$   
GeV/c  
 $|\eta| < 1.3$ , full  $\phi = 2\pi$   
merging & HBT  
cuts  
applied

# $\eta, \phi$ charge difference correlations for 62 GeV Au-

STAR <sup>Au</sup>  
preliminary



Gaussian to exponential opaque medium



p-p  
200 GeV

Evolution from 1D string fragmentation to at least 2D hadronization

Correlations & Fluctuations at MIT

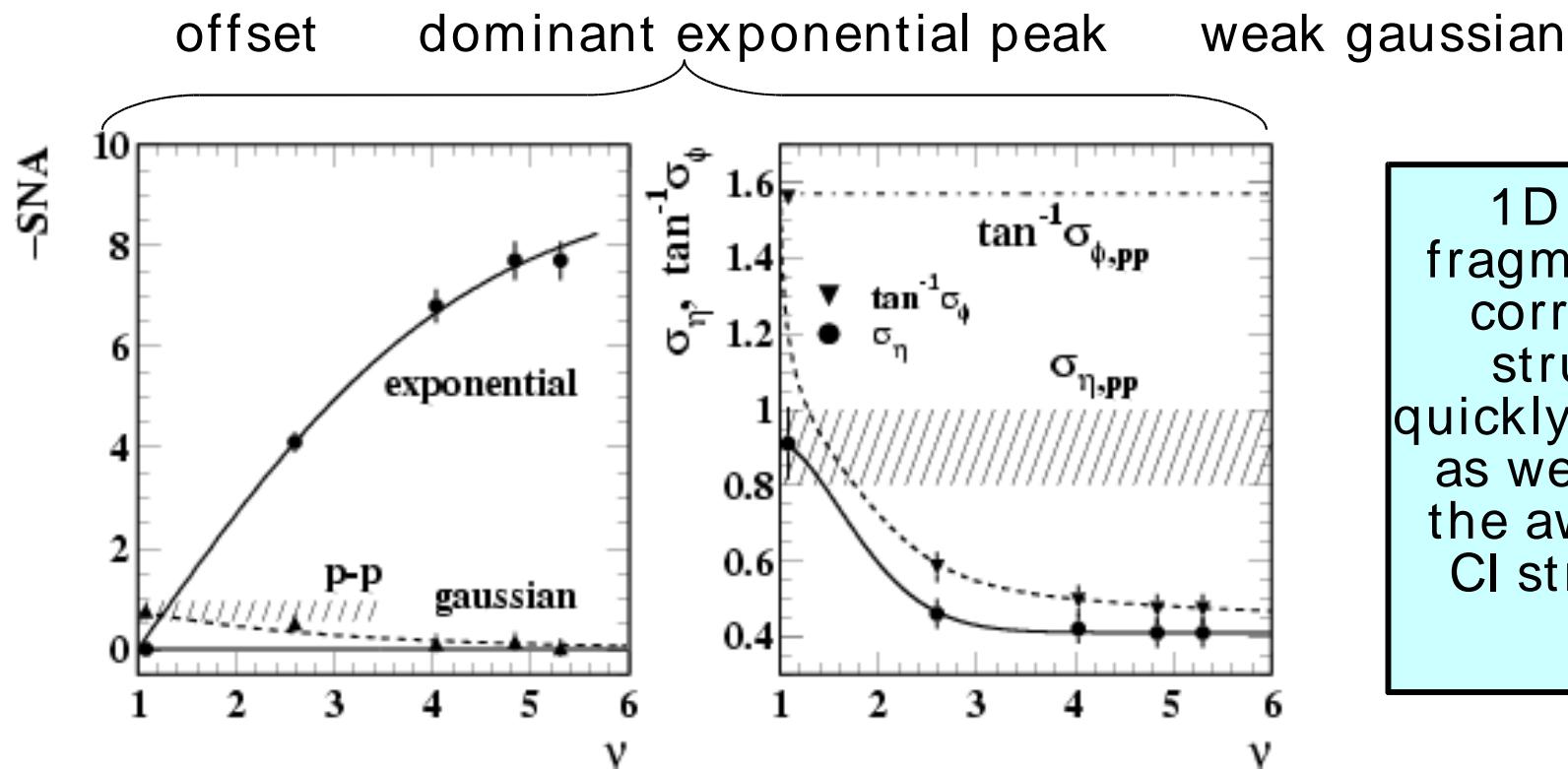
$0.15 < p_t < 2$   
GeV/c  
 $|\eta| < 1.0$ , full  $\phi = 2\pi$   
merging & HBT  
cuts  
applied 19

# Au- Au 130 GeV Like- Unlike Charge Difference – model fit

**Model Fit:**

$$F = A_0 + A_1 e^{-\left[\left(\frac{\phi_\Delta}{\sqrt{2}\sigma_{\phi_\Delta}}\right)^2 + \left(\frac{\eta_\Delta}{\sqrt{2}\sigma_{\eta_\Delta}}\right)^2\right]^{1/2}} + A_2 e^{-\left(\frac{\eta_\Delta}{1.5\sqrt{2}}\right)^2}$$

Lanny Ray, Corr. & Fluct. in RNC 2005



1D string fragmentation correlation structure quickly dissolves as we saw for the away-side CI structure.

...and approaches a 2D hadronization geometry, i.e. symmetric widths on  $\phi_\Delta$ , with exponential attenuation suggesting an opaque medium.

# Again, the idea is

**Model Fit:**

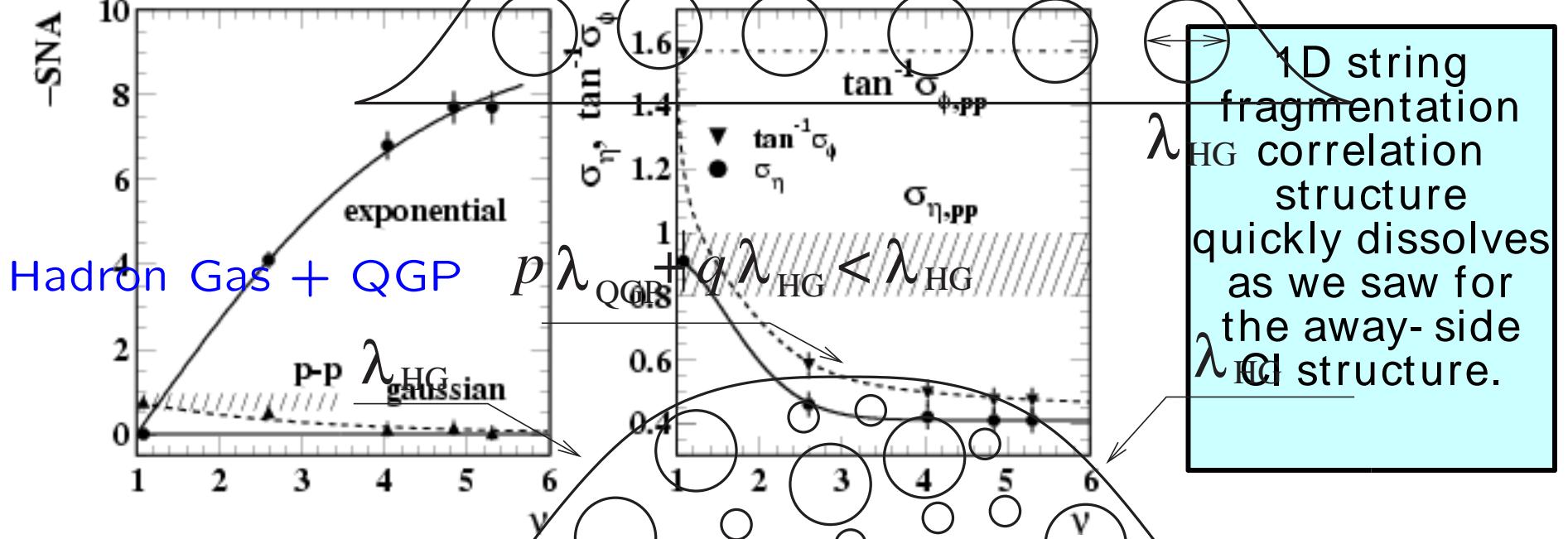
Hadron Gas only

$$F = A_0 + A_1 e^{-\left(\frac{\phi_\Delta}{\sqrt{2}\sigma_{\phi_\Delta 1}}\right)^2} + A_2 e^{-\left(\frac{\eta_\Delta}{\sqrt{2}\sigma_{\eta_\Delta 1}}\right)^2}$$

offset

dominant exponential peak

weak gaussian



...and approaches a 2D hadronization geometry, i.e. symmetric widths on  $\phi_\Delta$ , with exponential attenuation suggesting an opaque medium.